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Protection relay setting of the 6,6 kV motor feeder at LNG carrier

Nastavení ochranného relé napájení motoru 6,6 kV pro LNG

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Master Thesis

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-Desription of the motor protection terminal
-Short circuit calculation
-Protection function proposal and setting
-Conclusion

References:

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-Anderson, P.M.: Power system protection, IEEE Press 1999
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-IEC 61363 - 1 Electrical installations of ships and mobile and fixed offshore units –Procedures for calculating short-circuit currents in three-phase a.c.
-ABS - RULES FOR BUILDING AND CLASSING STEEL VESSELS 2019

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I hereby confirm the submission of the digital version of my thesis. I declare that I have written this thesis independently. I have listed all the literary sources and publications from which I have drawn my knowledge.

Date:________________ Signature:_______________

ABSTRACT AND KEYWORDS

ABSTRAKT

Vzhledem k velkému počtu motorů v námořních plavidlech je správný výpočet zkratových proudů a nastavení ochrany motoru zásadním konstrukčním úkolem zajišťující bezpečnost samotného plavidla, personálu, nákladu a vybavení; a zabránit abnormálnímu provozu palubního zařízení. Hlavními regulačními dokumenty jsou standardní pravidla IEC 61363 a pravidla ABS.

Hlavním úkolem je vypočet maximálních a minimálních zkratovych proudu na rozvaděčích LNG 6,6 kV se specifickou konfigurací, navrh potřebnych ochrannych funkci a jejich nastavení pro vybrané motory na základě příslušných námořních standardů a selektivity v celém MV systému představují všechny vypínací křivky.

KLÍČOVÁ SLOVA

Ochrana, námořní, LNG, nádoba, zkrat, zkratový proud, rozvaděč, motor, MV, ochranná funkce, konfigurace, výpočet, AC, DC, hodnota, vypnutí.

ABSTRACT

Due to the large number of motors in marine vessels, proper calculation of short-circuit currents and setting up a motor protection are vital tasks of engineering design in order to ensure safety of vessel itself, personnel, cargo and equipment; and prevent from abnormal operations of onboard installations. The main regulatory documents for that are standard IEC 61363 and ABS rules.

The main purpose of this thesis is to calculate maximum and minimum short-circuit currents at 6,6 kV switchboards of LNG carrier with specific configuration, propose necessary protection functions and its settings for chosen motors based on applicable marine standards and selectivity in the whole MV system, and also represent all tripping curves.

KEYWORDS

Protection, marine, LNG, vessel, short-circuit, short-circuit current, switchboard, motor, MV, protection function, configuration, calculation, AC, DC, value, tripping.

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LIST OF SYMBOLS AND ABBREVIATIONS

ABS – American Bureau of Shipping;

AC – Alternating Current;

CT – Current Transformer;

CSW – Cooling Sea-Water;

DC – Direct Current;

DC – Direct Current;

DT – Definite Time;

FSRU – Floating Storage Regasification Unit ;

HVCSB – High-Voltage Cargo Switchboard;

HD Comp. – High-Duty Compressor;

HMI – Human Machine Interface;

HVMSB – High-Voltage Main Switchboard;

HV – High-Voltage;

IDMT – Inverse Definite Minimum Time;

IEC – International Electrotechnical Commission;

IED – Intelligent Electronic Device;

LCD – Liquid Crystal Display;

LD Comp. – Low-Duty Compressor;

LED – Light-Emitting Diode;

LNG – Liquefied Natural Gas;

LV – Low-Voltage;

MV- Medium-Voltage;

PM – Propulsion Motor;

PTW – Power Tools for Windows;

RMS – Root Mean Square;

RTD – Resistance Temperature Detector;

SC – Short-Circuit;

SLD – Single-Line Diagram;

TCC – Time-Current Characteristic ;

TRMS – True Root Mean Square;

VT – Voltage Transformer;

LIST OF IMAGES AND CHARTS

1. ELECTRICAL PROTECTION IN MV-NETWORKS

1.1 INTRODUCTION

Selection of the protection system and relays depends on and related to with plant characteristics, type of industrial process and different requirements for service continuity , with the status of the neutral, characteristics of the machines, levels and duration of the fault currents, etc. An huge number of protections may also be harmful, since, even if they operate correctly in the case of a fault, they can operate in unnecessary moment when there is no fault, causing more or less widespread disturbance and out-of-order conditions, sometimes more severe than the faults themselves, as the cause cannot be found (even protections can operates wrong). It is important to emphasize, that trip selectivity must always be looked for, but only after having ensured protection of the network component. The protection relays are normally provided for different objectives, purposes and aims. In some cases a protection relay is used with the aim of activating automatisms to manage the electric network. The latter is a special application although normal in plants, but in this case the relays cannot be considered as network and plant protections [1-3].

The main objectives of protection relays are [2]:

– ensure safety and reliability of system;

– to provide the operator with an alarm indication in particular network or machine service conditions (for example, protection against negative sequence for generators);

– to put the line or faulty machine out of commission within a short time, as defined in the selectivity study;

– to carry out automatisms under particular service conditions (for example, undervoltage protections which activate automatic switching or automatic reclosing of the lines);

– control of the network parameters to prevent false operations (for example, synchronism check);

– to activate network parameter recording to memorise the network disturbances (for example, the starting contacts of the overcurrent relay);

– to carry out protection of the interface with the external network

Identification of the abnormal conditions is made by the protection relays, which operate to separate the faulty part of the network from the rest of the plant. The protection relay setting must be calculated to give the plant the highest possible service continuity to avoid damage to network components. The setting values must be selected above the transient conditions which can occur in the network without requiring disconnection.

1.2 BASIC OBJECTIVES OF SYSTEM PROTECTION

The fundamental purpose of system protection is provide isolation of a problem area in the power system quickly, so that the shock to the rest of the system will be minimized and as much as possible left intact. On this basis, there are six basic facets or aspects of protective relay application. It should be noted, that the word *protection* doesn't mean *prevention,* but rather, minimizing the duration of the trouble and limiting the damage, outage time, and related problems that may arise otherwise [2,3].

The five basic requirements for relay protections are [3]:

- *Reliability* – assurance that the protection will perform correctly when required to act. Two main aspects : 1) System must operate in the presence of fault that exists inside its zone of protection; 2) It must refrain from operating for faults outside its protective zone or if the fault does not exist.
- *Selectivity* – maximum continuity of service with maximum system disconnection. Only those protective devices closest to a fault will operate to remove the faulted component.
- *Speed and time* – the protective scheme must disconnect the faulty part of the system as soon as possible. If the faulty part takes more time to disconnect, it may damage the component which is carrying faulty current.
- *Simplicity* – minimum protective equipment and associated circuity to achieve the protection objectives.
- *Sensitivity* – the ability of the system to identify an abnormal condition that exceeds a nominal "pickup" or detection threshold value and which initiates protective action when the sensed quantities exceed that threshold.
- *Economics* – maximum protection at minimal total cost.

1.3 RELAY TYPES

There are a lot of ways how to distinguish and classify relay types, such as function, performance characteristics, operating principles. Classifications by function and system protection will be considered.

1.3.1 CLASSIFICATION BY FUNCTION

Five basic functional types are distinguished [3] :

- *Protective relays* operate on the unacceptable power system conditions. They are applied to all parts of the power system : generators, transformers, buses, transmission and distribution lines, feeders, motors capacitor banks and reactors as well.
- *Regulating relays* – relays which are associated with tap changers on transformers and on voltage regulators of generating equipment to control voltage levels with varying loads. They are used during normal system operation and don’t respond to system faults unless the faults are left on the system far too long.
- *Reclosing, synchronism check and synchronizing relays* are used in energizing or restoring lines to services after an outage
- *Monitoring relays* are used to verify conditions in the power system or in the protective system.
- *Auxiliary relays* are generally used for contact multiplication and circuit isolation. It is a relay that assists another relay or device in performing an action. It implements this when its operating circuit is opened or closed. These relays are used in nearly all electronic devices to assist them in functioning correctly. Essentially, it is as simple as an action done to the relay causing the opening of circuit — or closed and not allow power to pass through it.

1.3.2 CLASSIFICATION BY THE PURPOSE OF SYSTEM PROTECTION

For the purpose of system protection, relays are classified according to the following statements [3]:

- *Overcurrent and overvoltage relays* – relay, which are operates when current or voltage exceeds a predetermined value
- *Differential relay* - relay, which is intended to respond to the difference between incoming and outgoing electrical quantities or signals connected with protected apparatus.
- *Distance relay* - is name given to the protection, whose action depends on the distance of the feeding point to the fault. The time of operation of this protection is a function of the ratio of voltage and current, i.e., impedance. This impedance between the relay and the fault depends on the electrical distance between them.
- *Directional relay* – a relay which operates to the relative phase position of a current with respect to another current or voltage reference
- *Pilot protection* - a form of line protection that uses a communication channel as a tool of comparing electrical quantities at the terminals of the line.

1.4 PROTECTION OF MOTOR CIRCUITS

Overload and short-circuit current protection must be provided for each motor circuit in accordance with the following requirements [5] :

1) *Motor branch circuit protection* .

Motor branch circuits must be protected with circuit breakers or some fuses, which have both instantaneous and long-time delay trips. Settings must be such that they will permit the passage of starting currents without tripping. Typically, the protective device must be set in excess of the motor's full load current but not more than the limitations given in the table below. If that rating or setting is not available, the next higher available rating or setting may be used. In cases where the motor branch circuit cable has allowable current capacity in excess of the motor full load current, the protective device setting may exceed the applicable limitation. If the motor branch is protected with a circuit breaker fitted with instantaneous trip only , the motor controller must have a short-circuit rating matching, at least, with the circuit breaker instantaneous trip setting, and the motor overload protection must be designed to open all conductors.

Trip elements for starting and short-circuit protection must comply with the requirements in Table 1, except that some circuit breakers which have only instantaneous trips might be provided as a part of motor control center. Where circuit breakers having only instantaneous trips are provided, the motor protection device must open all the conductors, and the motor running protective device must be able to open the circuit without damaging itself as a resulting from a current before setting of the circuit breaker.

According to general ABS requirements [4,5] and documentation, the maximum fuse rating or setting of the trip element must be the value which is stated below. If that rating or setting is not available, the next higher available rating or setting might be used.

Table 1 – Limitations of the motor's full-load current

Type of Motor	*Rating or Setting, % Motor Full-load Current*
Squirrel-cage and synchronous full-voltage, reactor or resistor starting	250
Autotransformer starting	200
Wound rotor	150

When fuses are used to protect polyphase motor circuits, it has to be arranged to protect against single-phasing.

The setting of magnetic instantaneous trips for short-circuit protection only is to exceed the transient current inrush of the motor, and is to be the standard value nearest to, but not less than, 10 times full-load motor current.

Running protection is must be provided for all motors having a power rating exceeding 0.5 kW, except that such protection is not to be provided for steering motors . The running protection must be set between 100% and 125% of the motor rated current.

Undervoltage protection is to be provided for motors having power rating exceeding 0.5 kW (0.7 hp) to prevent undesired restarting upon restoration of the normal voltage, after a stoppage due to a low voltage or voltage failure condition.

Special attention must be paid to the starting currents due to a group of motors with undervoltage release controllers being restarted automatically upon restoration of the normal voltage. Means such as sequential starting is to be provided to limit excessive starting current, where it is necessary [5].

2) Motor Overload protection

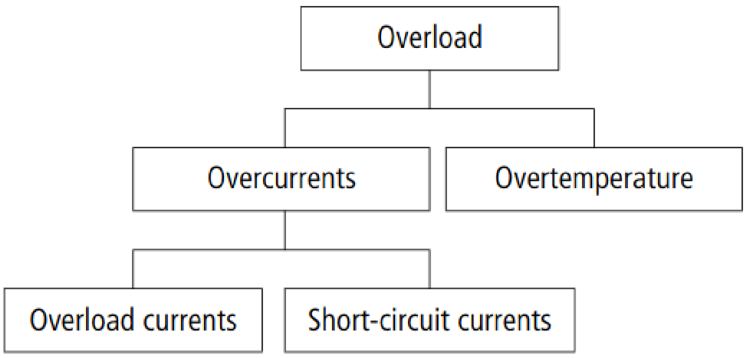


Figure 1 – Different categories of overload

The overload protective devices of motors must be compatible with the motor overload thermal characteristics and set at 100% of the motor rated current for continuous rated motor. If this is not practicable, the setting may be increased to some value which does not exceed 125% of the motor rated current. This overload protective device may also be considered as the overload protection of the motor branch circuit cable.

ABS regulates overcurrent and overload capacity in this way [4,5]:

- Three-phase motors, except for commutator motors, having rated outputs not exceeding 315 kW and rated voltages not exceeding 1 kV are to be capable of withstanding a current equal to 1.5 times the rated current for not less than two minutes. For three-phase and single phase motors having rated outputs above 315 kW, the overcurrent capacity is to be in accordance with the manufacturer's specification. The test may be performed at a reduced speed.
- Three-phase induction motors are to be capable of withstanding for 15 seconds, without stalling or abrupt change in speed, an excess torque of 60% of their rated torque, the voltage and frequency being maintained at their rated values

IEC60947 specifies the exact requirements for of overload releases on motor-protective circuit-breakers or motor protective relays in order to prevent the continuous thermal overload of motor: At a temperature of 20 ℃, an overload release must not trip within two hours starting from cold when there is a 5% overcurrent at all three poles. If the current is increased to 120 % of the rated current afterwards, the relay must trip within two hours. This requirement assumes a continuous loading of the rated current [12].

2. SHORT-CIRCUIT CALCULATION THEORY

The main distribution network in marine application is 690 V for LV and 6.6 or 11 kV for MV.

Marine and offshore applications have LV and MV power networks. The main distribution network in marine application is:

- LV (690 V)
- MV (6.6 or 11 kV)

Main distribution network is either with isolated neutral point or neutral point earthed through high-resistance. Lower voltage levels such as 440 V and 230 V are normally isolated.

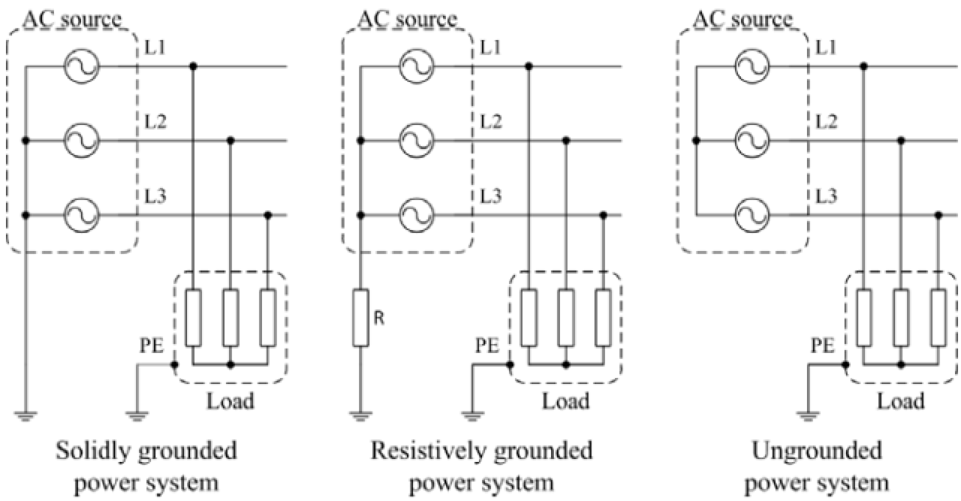


Figure 2 - Grounded and ungrounded power systems

Some types of faults may occur in any power system, such as :

- Open-circuit faults
- Short-circuit faults
    - Phase faults
    - Ground faults
- Other abnormal conditions
    - Under-excitation
    - Overloading
    - Active power shortage
    - Loss of synchronism
    - Mechanical defects

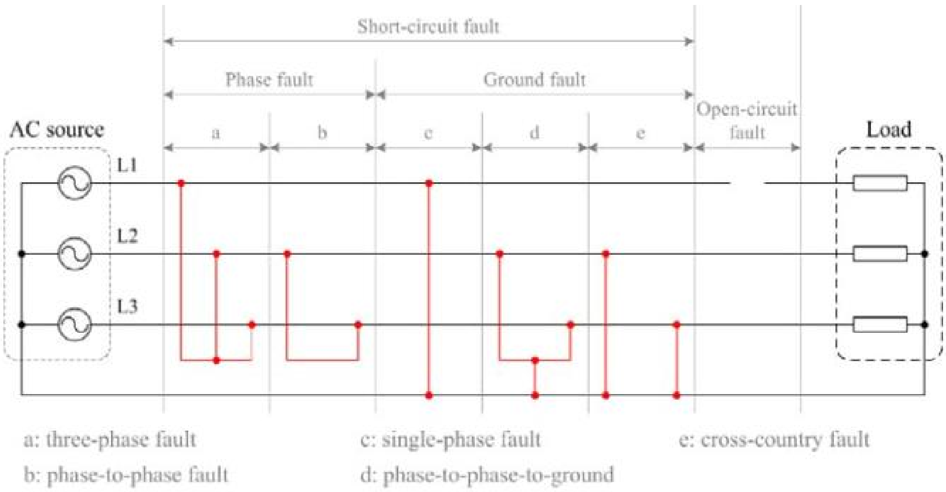


Figure 3 - Basic electrical faults in three-phase power systems occurence

In this chapter some short-circuit calculation features are considered in more detail. It is impossible always to prevent or protect systems from short-circuit occurrence. Engineers and designers are able to facilitate or reduce potentially destroying effects only, so that the occurrence of short-circuit becomes minimal and insignificant. In case if short-circuit occurs, isolating the smallest possible portion of the system around the faulted area in order to save the rest of the system and managing the magnitude of undesirable fault current, are strictly required.

Interrupting equipment at all voltage levels that is capable of withstanding the fault currents and isolating the faulted area requires considerable investments. Therefore, the main reasons for performing short-circuit calculations are follows :

- Defining system protective device settings and that is done by quantities that describe the system under fault conditions.
- Verification of the adequacy of existing interrupting equipment.
- Analysis of the effect that different kinds of short circuits of different severity may have on the overall system voltage profile. These calculations identify areas in the system for which faults can lead to unacceptable voltage drops.
- Defining effects of the fault currents on various system components such as cables, overhead lines, buses, transformers, capacitor banks and reactors during the time the fault remains. Mechanical stresses from the resulting fault currents are compared with the corresponding short-term withstand capabilities of the system equipment.
- Design and sizing of system layout, neutral grounding, and substation grounding.

In terms of short-circuit analysis, system faults manifest themselves as insulation breakdowns which leads to the following phenomena :

- Currents of excessive magnitudes that usually cause equipment damage
- Undesirable power flow
- Voltage drops
- Excessive over-voltages
- Cause conditions that could harm personnel or put people’s life at risk

2.1 REQUIREMENTS FOR SHORT-CIRCUIT STUDIES AND CALCULATIONS

The requirements of a short-circuit study will depend on the set aims. These aims will dictate what type of short-circuit analysis is required. The amount of data required will also depend on the extent and the nature of the study. The majority of short-circuit studies in industrial and commercial power systems review one or more of the following four kinds of short circuits :

1) Line-to-line fault (Any two phases are shorted together)
2) Double line-to-ground fault. (Any two phases connected together and then to ground)
3) Single line-to-ground fault. (Only one, phase shorted to ground).
4) Three-phase fault. May or may not involve ground. (All three phases are shorted together)

It should be mentioned that three-phase short-circuit is the most dangerous and severe fault for power system and equipment, so only three-phase calculations are implemented when searching for the maximum possible magnitudes of fault currents. However, some exceptions exist. This exception – single line-to-ground short-circuit currents which can exceed three-phase short-circuit currents, if they occur in surrounding of :

1) The solidly grounded star side of a delta-star transformer of the three-phase core design
2) The grounded star side of a delta-star autotransformer
3) A solidly grounded synchronous machine
4) The grounded star, grounded star, delta-tertiary, three-winding transformer

In case if above-mentioned conditions do exist, it is really desirable to perform a single line-to-ground fault calculation. Line-to-line or double line-to-ground fault calculations might also be necessary for protective device setting up and coordination requirements. Furthermore, because only one phase of the line-to-ground fault can experience more significant interrupting requirements, the three-phase fault will still contain more energy because all three phases will need the same.

Case when one-phase short-circuit current is higher than three-phase is very special and rare and not applicable to marine sector.

A marine and offshore structure electrical system should be designed to ensure that all possible precautions have been taken to prevent short-circuit currents occurring. The principal objective of calculating the short-circuit current is to ensure that the system and its components are capable of withstanding the effects of the short-circuit conditions, and thereby limit any resulting damage to a minimum. System short-circuit current protection is normally provided by fuses and circuit-breakers. The principle intent of these calculations is to provide sufficient information to enable such devices to be selected with confidence that they are capable of providing the necessary protection. In addition, the calculations may be used to help select devices capable of limiting the short-circuit current to within the capabilities of the protective devices [5,7].

2.2 BASIC DIFFERENCES BETWEEN IEC 60909 AND IEC 61363 STANDARDS

Generally, IEC 60909 is usually used for short-circuit calculations in industrial premises and enterprises. It is applicable for meshed and unmeshed networks, for three-phase as well as unsymmetrical faults, for far and close to generator faults. IEC 61363, in turn, used for marine application, isolate offshore facilities, plants and installations [6,7].

The IEC 61363 considers the attenuation of short-circuit currents produced by generators and motors in subtransient and transient modes and takes into account the effect of external line impedance on the time constant. When the ship power system is connected to the shore power and becomes a part of the land power grid, the short-circuit current analysis may be carried out according to IEC 60909. In this method, the equivalent voltage source is modeled as the unique actuation voltage of the system, such as the shore power supply, and the generators and motors on ships are modeled as internal impedance [7].

Marine and offshore electrical systems typically have large generating capacities confined in a small area resulting in high short circuit values with low power factors. Special attention is required if the calculated power factor during fault conditions is below the power factor used to test the circuit breakers [5,7].

Table 2 – Differences between IEC 60909 and IEC 61363

Criterions	**IEC 60909**	**IEC 61363**
Calculation method	- The method used for calculation of short-circuit currents is based on introducing of an equivalent voltage source right at the short-circuit point or location. This equivalent voltage source represents only <u>*active voltage*</u> in the system. It means that all feeders, synchronous and asynchronous machines are replaced by their internal impedances. So, this equivalent voltage source replaces ALL voltage sources. - Allows to calculate asymmetrical currents	- Takes into consideration ALL sources independently - System is divided into both *active and non-active* components. Active components – sources of short-circuit current, non-active components, in turn, transmit the SC-current and distribute it from the source to fault point. - Calculates the symmetrical short-circuit current only
Application	- Low-voltage three-phase AC systems - High-voltage three-phase AC systems *Does not deal with short-circuit current calculations in installations, facilities on board ships and aeroplanes*.	- Unmeshed three-phase alternating current systems only *Does deal with short-circuit current calculations in marine or offshore AC electrical installations*
Simplifications and assumptions	Calculations assumptions and simplifications are basically the same but in *IEC61363* some other statements are taken into consideration, such as: 1) At the starting point of the short-circuit, the instantaneous value of voltage in one phase at the fault point equals to zero 2) For generators connected in parallel, all generators share their active and reactive load proportionally at the start and during the short-circuit.	

Additional notes	- Computing of the short-circuit impedance is in general based on the rated data of the electrical equipment and topological structure of the system - Generally, two short-circuit currents which has different magnitude can be calculated : 1) maximum short-circuit current which determines the productivity or performance of electrical equipment; 2) minimum short-circuit current which can be the framework for fuses selection, setting up of different protective devices, and for checking the running start of motors. - In case of accidental or intentional conductive path between one line conductor and local earth, the following two cases must be clearly distinguished according to their different physical properties and effects: • Line-to-earth short-circuit, occurring in a solidly earthed neutral system or an impedance earthed neutral system • Single line-to-earth fault, occurring in an isolated neutral earthed system or a resonance earthed neutral system. This fault is not considered in this standard. - There are several DC-current time constants in meshed networks. That is why it is not possible to give an easy method of calculating i_p and $i_{d.c}$	- The calculation procedures are for a three-phase symmetrical short-circuit condition i.e. three phase conductors shorted together, or shorted to the ship's hull and for which the short-circuit occurs on all three poles simultaneously. The calculation of short-circuit currents resulting from asymmetric short-circuit conditions can lead to higher aperiodic components of the short-circuit current and ***they are not considered in this standard***. - Accurate results will be produced to calculate the short-circuit current during first 100 ms of a faiut condition. Calculating of short-circuit currents for periods which are longer than 100 ms are suitable when calculating on a bus systém to which the generators are directly connected. For those time periods (beyond 100 ms) controlling effects of the systém voltage regulators might be predominant. - The majority of marine/offshore electrical systems are operated with the neutral point insulated from the hull or connected to it through an impedance. In such systems, the highest value of short-circuit current is the three-phase short circuit. If the neutral point is directly connected to the hull, then the line-to-line to ship's hull, or line-to-ship's hull short circuit may produce a higher current.

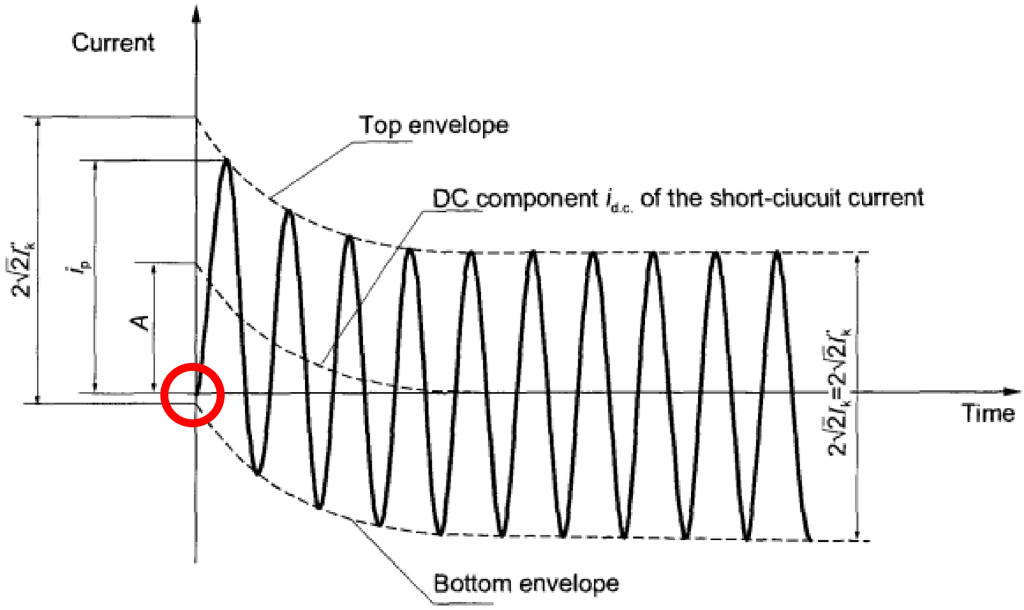


Figure 4 – Short-circuit current of a far-from-generator short circuit with constant AC component (IEC 60909)

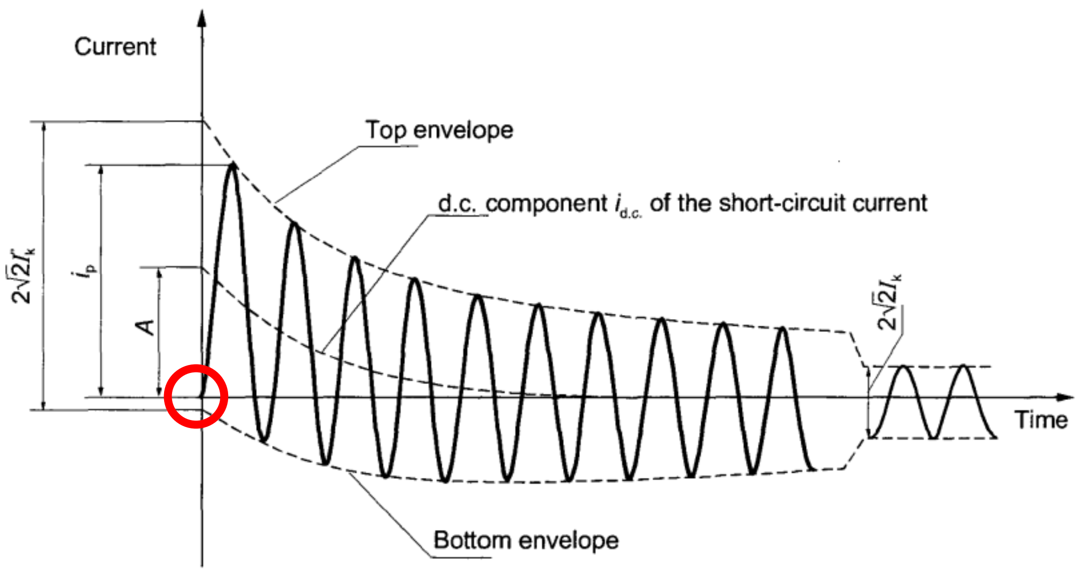


Figure 5 – Short-circuit current of a near-to-generator short circuit with decaying AC component (IEC 60909)

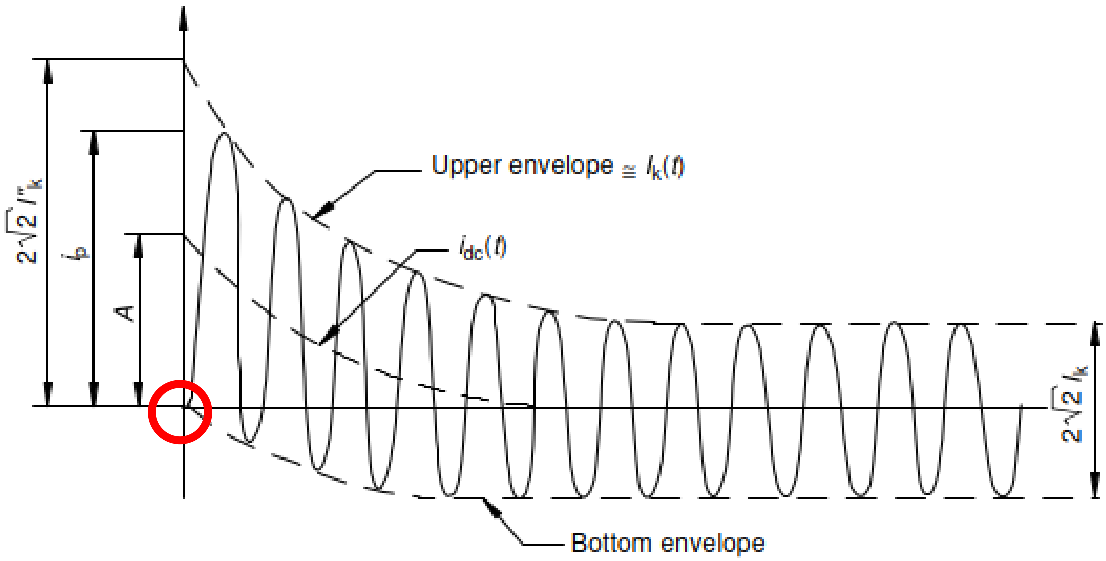


Figure 6 – Synchronous generator terminal short-circuit current time function (IEC 61363)

I''_k – initial symmetrical short circuit current ;

i_p – peak short-circuit current ;

I_k – steady-state short-circuit current ;

$i_{d.c.}$ – decaying component of short-circuit current ;

A – initial value of the aperiodic component ;

Comparing these two current-time dependencies, it should also be noted that there is a difference between starting point of the current curve in both cases. It is marked as a *red circle*. It starts from zero in second case (Figure 6) and bottom envelope starts from this point respectively.

The reason is that the highest value i_p, depends on the time constant of the decaying aperiodic component and the frequency *f*, that is on the ratio *R/X* or *X/R* of the short-circuit impedance Z_k, and is reached if the short circuit starts at zero voltage. I_p also depends on the decay of the symmetrical AC component of the short-circuit current [6], but IEC 60909 unlike IEC 61363 does not take into account the fact that at the start of short-circuit, the instantaneous value of voltage in one phase at the fault point is zero [7].

3. DESCRIPTION OF THE MV DISTRIBUTION NETWORK AT LNG VESSEL

In order to make the sea transport of natural gas effective, and therefore economically reasonable, natural gas needs to be converted into liquid, known as Liquefied Natural Gas (LNG). The liquefaction of natural gas is possible by lowering the temperature of the gas to –163 ℃. The cooling process occurs at complex liquefaction plants located at deep sea ports and connected to the gas fields by pipeline. In that liquid state, the LNG is then transferred into an LNG carrier. In order to safely transport 180,000 m^3 of gas at –163 ℃ across the ocean, LNG carriers have complex, comprehensive and unique systems – for example, cargo containment, cargo cooling, regasification, electrical propulsion, etc – everything that must comprise and contain a technologically advanced vessel.

Since that time, LNG carriers are becoming a great part of the natural gas logistics and transportation chain. Therefore, they are obliged to comply with requirements of reliability, so that gas will be delivered on time without compromising safety of life, environment, cargo, etc.

3.1 LNG TYPICAL ELECTRIC POWER AND PROPULSION CONFIGURATION

Complete single-line diagram of 6,6 kV Main&Cargo Switchboards are shown in Appendix I.

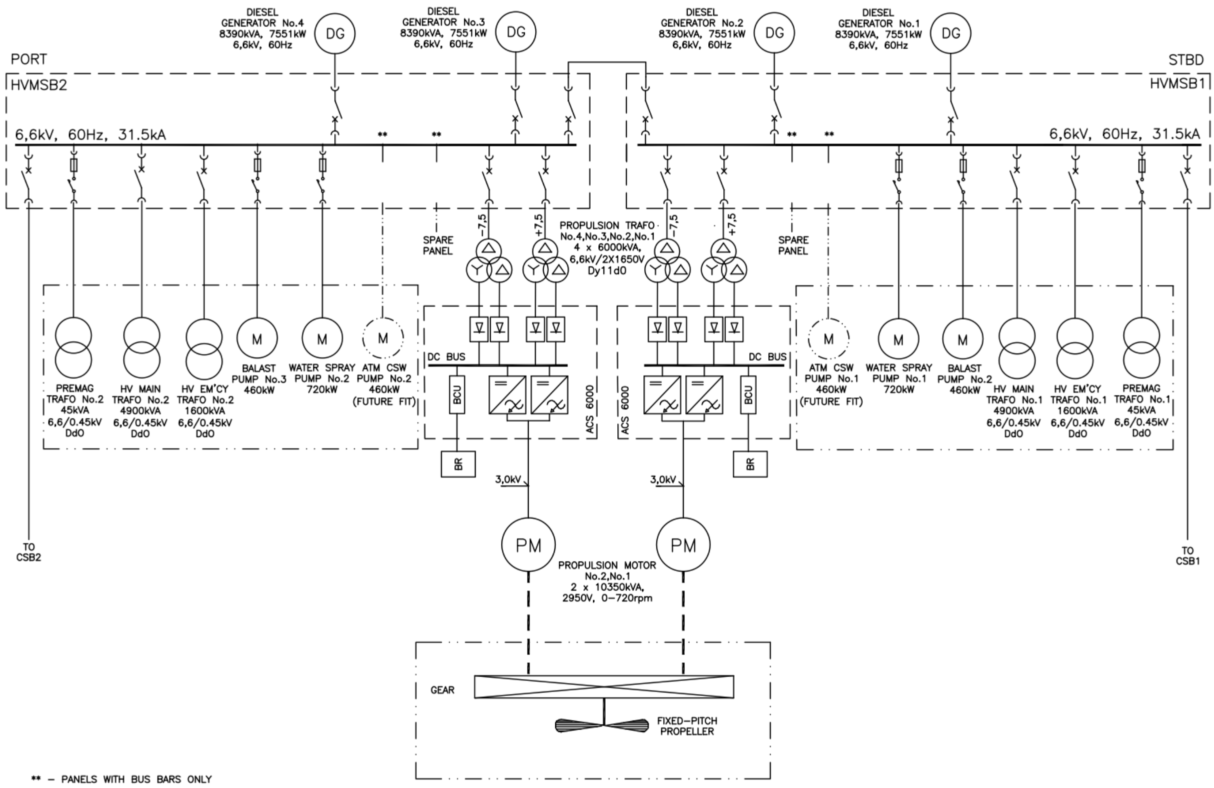


Figure 7 – SLD of 6,6 kV Main Switchboards

For the LNG regasification FSRU vessel is intended. Diesel engines on board of LNG carrier are dual fuel engines, which means it can combust heavy oil as primary fuel and also the gas producing as a result of vaporization on upper part of LNG transportation tanks.

Main distribution system of LNG carries is typical and consists of four 6,6 kV switchboards – two main switchboards and two cargo switchboards. Both main and cargo switchboards might be connected by means of busties (transfers)**,** however ring connection is not allowed.

Typical configuration of this systém is in the Figure 3 . Generally, there are four engines in the range between 5 and 12 MW, system voltage is 6,6 kV.

Typically, electric power configuration of LNG carrier represents network with two High Voltage Main Switchboards and two High Voltage Cargo Switchboards (it is called as *High Voltage* in marine application but physically it is *Medium Voltage*) with the following equipment :

- Diesel Generators
  - Four Diesel generators 8390 kV, 7551 kW (two generators to each HVMSB)
- Ballast pumps motors, which pump water in and out of ballast reservoirs
  - Two Ballast Pumps 460 kW

  Ballast pumps plays a significant role in operating of most vessels. They delivery water in and out of the ballast water tanks; when it is loading, off-loading and balancingfilled of the vessel. The ballast is generally seawater. It is pumped into tanks known as ballast tanks. These tanks are filled by the ballast pump in order to add weight to the ship. When cargo has been offloaded, it is used to improve vessel's stability.
- Four distribution transformers 6,6/0,45 kV
  - Two HV main TRAFO Transformers 4900 kVA (main distribution transformers)
  - Two HV TRAFO Transformers 1600 kVA (emergency distribution transformers)
- Four three-winding propulsion Transformers 6,6 kV/2x1650 V
  - Four TRAFO Propulsion Transformers 6000 kVA
- Main propulsion frequency converters
  - Two Drives ACS6000

  The ACS6000 MV drive is part of ABB's special purpose drives portfolio. These drives are suitable for high power, high speed or special performance applications such as test stands, marine propulsion and thrusters, rolling mills, large pumps, fans and compressors
- Propulsion Motors
  - Two Propulsion Motors 10350 kVA
- Cargo Pumps motors, which pump LNG in and out of tank
  - Two Water Spray Pumps 720 kW

  Sprayer pumps are designed to push or pull fluid tank contents out to a spray nozzle(s) at specific gallons per minute (GPM) flow rates and pressure delivery.
  - Two CSW Pumps 460 kW

  Cooling Sea Water Pumps are designed to deal with wastewater and other non-corrosive liquids with soft solids in suspension

All of the following equipment is connected to HVCSBs :

- Cargo Transformers 6,6/0,45 kV
  - Two HV Cargo TRAFO Transformers 2800 kV
- Cargo Pumps motors, which pump LNG in and out of tank
  - Eight Cargo Pumps 370 kW
- Low Duty and High Duty compressors motors, which ensure sufficient temperature in cargo tanks
  - Two HD Compressors 1090 kW

High duty compressors are installed in the compressor room on deck and are routinely used for compressing the LNG vapour for return to shore during cargo tank initial cool down, cargo loading, tank purging and to circulate heated cargo vapour through the tanks during warming up.

- Two LD compressors 720 kW

Low duty compressors are installed in the compressor room on deck and are routinely used for compressing the LNG vapour produced by natural boil-off to a sufficient pressure to be used in the boilers as fuel.

- Four GWC Pumps 586 kW

- Condensing pump - is a specific type of pump used to pump the condensate (water) produced in heating or cooling, refrigeration, condensing boiler furnace or steam system. It may be used to pump the condensate produced from latent water vapor

- Four Sea Water Pumps 1100 kW
- Eight LNG BSTR Pumps 1400 kW

HVMSB1 is connected with HVCSB1 and HVMSB2 with HVCSB2, respectively.

4. DESCRIPTION OF THE MOTOR PROTECTION TERMINAL

REM615 relay has been chosen for further calculations and analysis. It is motor protection and control relay, designed by ABB, for protection, control, measurement and supervision of asynchronous motors in different variations of industries.

Typically, the motor relay is used with circuit breaker and contactor-controlled MV motors and medium-sized and large contactor-controlled LV motors in a variety of drives. The drives include both continuously and periodically operated asynchronous motor drives with varying loads.

Main highlights : 1) Motor protection both during motor start-up and normal operation mode, with protection and fault detection also in abnormal situations ; 2) Motor protection with motor start-up and loss of load control as well as thermal overload, motor load jam and phase-reversal protection, either with sensors or regular instrument transformers [7,8].

REM615 is available in four standard configurations [10] :

1) Configuration A - Basic motor protection

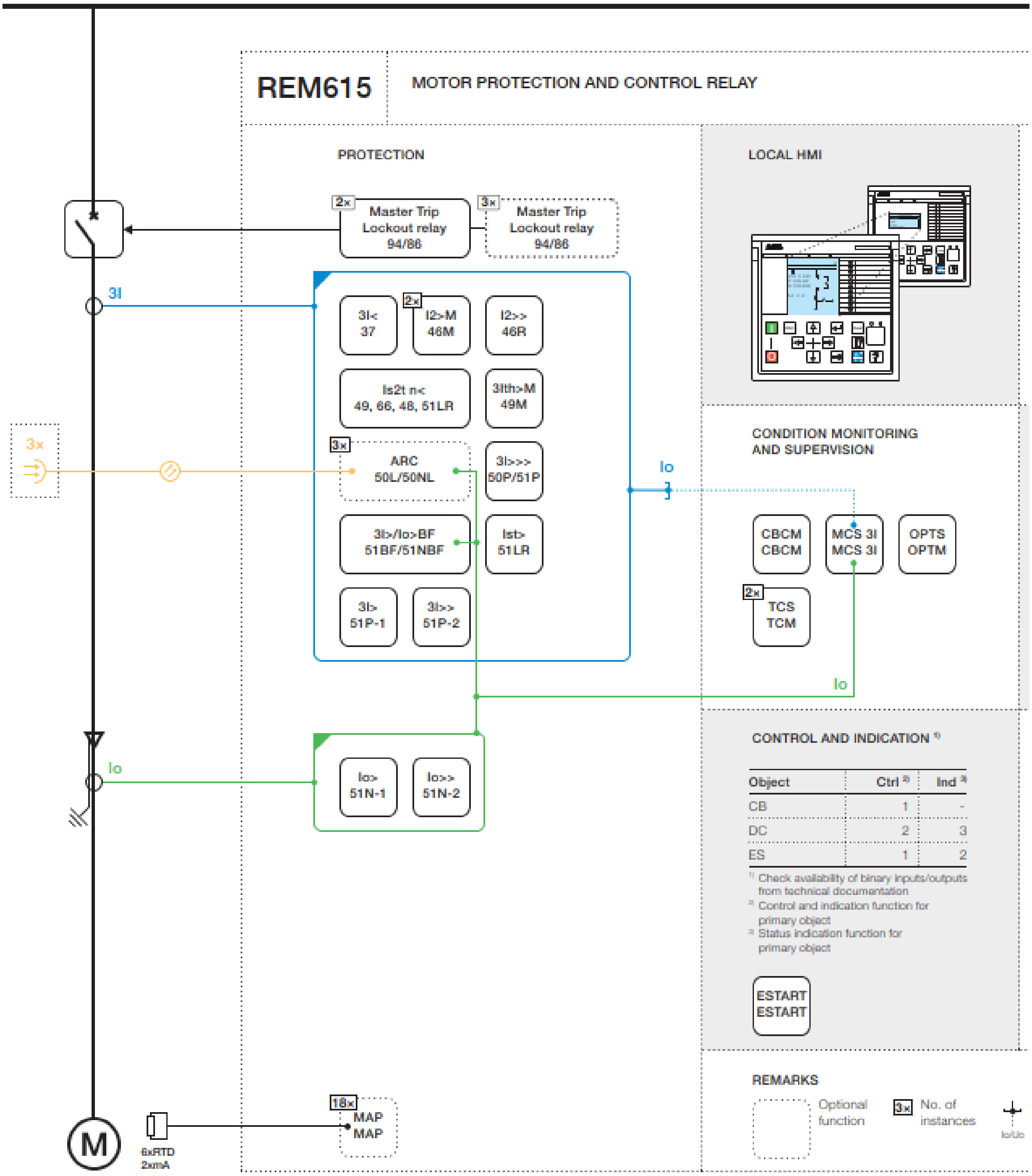


Figure 8 – Functionality overview of standard configuration A

4.1 PROTECTION FUNCTIONS

The relay includes non-directional earth-fault protection, negative phase-sequence current unbalance protection and backup overcurrent protection. Moreover, the relay offers motor running delay protection, loss-of-load supervision and phase reversal protection.

The RTD/mA module offered as an option for standard configurations A and B enables the use of the optional multipurpose protection function for tripping and alarm purposes using RTD/mA measuring data or analog values [8].

Table 3 – Functionality of REM615

Functionality	***REM615***
Control	✓
Overcurrent protection	✓
Earth-fault protection	✓
Thermal overload protection	✓
Multipurpose protection with RTD/mA	+
Basic voltage protection for motor	✓
Frequency protection	✓
Protection for asynchronous motors	✓
Arc protection	+

✓ supported functions + Optional add-on functions

In some motor drives of special importance there must be a possibility to redefine the motor thermal overload protection to perform an emergency start of a hot motor. To enable an emergency hot start, REM615 offers a forced start function.

Enhanced with optional hardware and software, the relay also includes three light detection channels for arc fault protection of the circuit breaker, busbar and cable compartment of nclosed indoor switchgear.

The arc-fault protection sensor interface is available on the optional communication module. Fast tripping increases safety of staff and security and limits damage in an arc fault situation. A binary input and output module can be selected as an option - having three high speed binary outputs it further decreases the total operate time with typically 4-6 ms compared to the normal power outputs [8]

4.2 CONTROL FUNCTIONALITY

REM615 includes functionality for the control of a circuit breaker via the front panel HMI or by means of remote controls. In addition to the circuit breaker control the relay represents two control blocks which are designed for motor-operated control of disconnectors or circuit breaker truck and for their position indications. Further, the relay offers one control block which is designed for motor-operated control of one earthing switch control and its position indication.

The optional large graphical LCD of the relay's HMI includes a single-line diagram (SLD) with position indication for the relevant primary devices. Interlocking schemes required by the application are configured using the signal matrix or the application configuration functionality of PCM600.

The relay is provided with a load profile recorder. The load profile feature stores the historical load data captured at a periodical time interval (demand interval).

By default, the binary channels are set to record external or internal relay signals (the start or trip signals of the relay stages or external blocking or control signals.) Protection start and trip signals and an external relay control signal can be set to initiate the recording via a Binary input. Recorded information is stored in a nonvolatile memory and can be uploaded for subsequent fault analysis [9,10].

4.3 MEASUREMENT FUNCTIONALITY

The main task of this relay - continuous measuring of the phase currents and the neutral current. Furthermore, the relay measures the phase voltages and the residual voltage. Depending on the standard configuration, the relay also can measure frequency. Also, the relay calculates the symmetrical components of the currents and voltages, maximum current demand value during the pre-set time, selected by user, the active and reactive power, the power factor and the active and reactive energy values. Calculated values are also obtained from the protection and condition monitoring functions of the relay. The measured values can be accessed via the local HMI or remotely via the communication interface of the relay. The values can also be accessed locally or remotely using the Web HMI [9,10].

4.4 SUPERVISION FUNCTIONALITY

The relay includes three important functions of supervision :

1) Self-supervision. Relay’s self-supervision system, which is embedded in the device, continuously monitors the state of the relay hardware and the operation of the relay software.

2) The fuse failure supervision. It detects faults between the voltage measurement circuit and the relay. Upon detection, the fuse failure supervision function activates an alarm and blocks voltage-dependent protection functions from unintended operation.

3) The current circuit supervision. It is used for detecting faults in CT secondary circuits. Upon detection of a fault, the current circuit supervision function activates an alarm LED and blocks certain protection function to avoid or prevent unintended operations. A permanent relay fault blocks the protection functions to prevent incorrect operations [9,10].

5. SHORT-CIRCUIT CURRENT CALCULATION

5.1 DESCRIPTION OF SOFTWARE

SKM Power Tools for Windows has been chosen for short-circuit current calculations. SKM is the leader in power systems analysis and design software for fault calculations, load flow, coordination, arc flash hazards, motor starting, transient stability, reliability, harmonics, grounding, cable pulling, etc. SKM software has been used in commercial, light and heavy industrial, institutional, utility sites and facilities worldwide [13].

One of the biggest advantage of SKM is that it could be easily orientated to SC calculations according to IEC 61363 which is the main standard for marine and offshore installations.

The IEC 61363 Short Circuit study represents conditions that may affect typical marine or offshore installations more significantly than land-based systems, due to more emphasis on generator and motor decay. The calculation methods are intended for use on unmeshed three-phase AC systems operating at 50 Hz or 60 Hz; having one or more different voltage levels; comprising generators, motors, transformers, reactors, cables and converter units; having their neutral point connected to the ship's hull through an impedance; or having their neutral point isolated from the ship's hull [13].

SKM is able to represent all necessary TCCs automatically and set up a relay protection for equipment right in this window, where all characteristics of equipment from the chosen path of protection (from generator to protected object) are shown . Relay protection curve might be set up via both calculation methods and manual moving of protective curve for harmonization and coordination.

5.2 MODELLING OF THE POWER SYSTEM

6.6 kV Main&Cargo switchboards and its equipment have been modelled in SKM (see Figures 9,10).

The main task of that modelling is to calculate maximum and minimum short-circuit currents at each switchboard for further use in setting up a relay protection according to different protection functions.

In order to obtain maximum short-curcuit currents, ring configuration must be disconnected in some point. As it it shown in Figure 9, Cargo-Cargo transfer is out of service; the rest Main-Main and two Main-Cargo transfers are in service. All power sources such as generators, motors, transformers, lines are considered and taken into account : namely 4 generators, 34 motors and 10 transformers.

In order to obtain minimum short-circuit currents, all generators and motors must be disconnected and its contribution is excluded from calculation. Generators are replaced by Utility Power with current three times nominal current of generator as the Automatic Voltage Regulator limits sustained current to $3 \cdot I_n$ (see Figure 10).

All calculation results are given right in Figures 9,10 and Tables 4,5. Input data for cables and all equipment is given in Appendices II-VI.

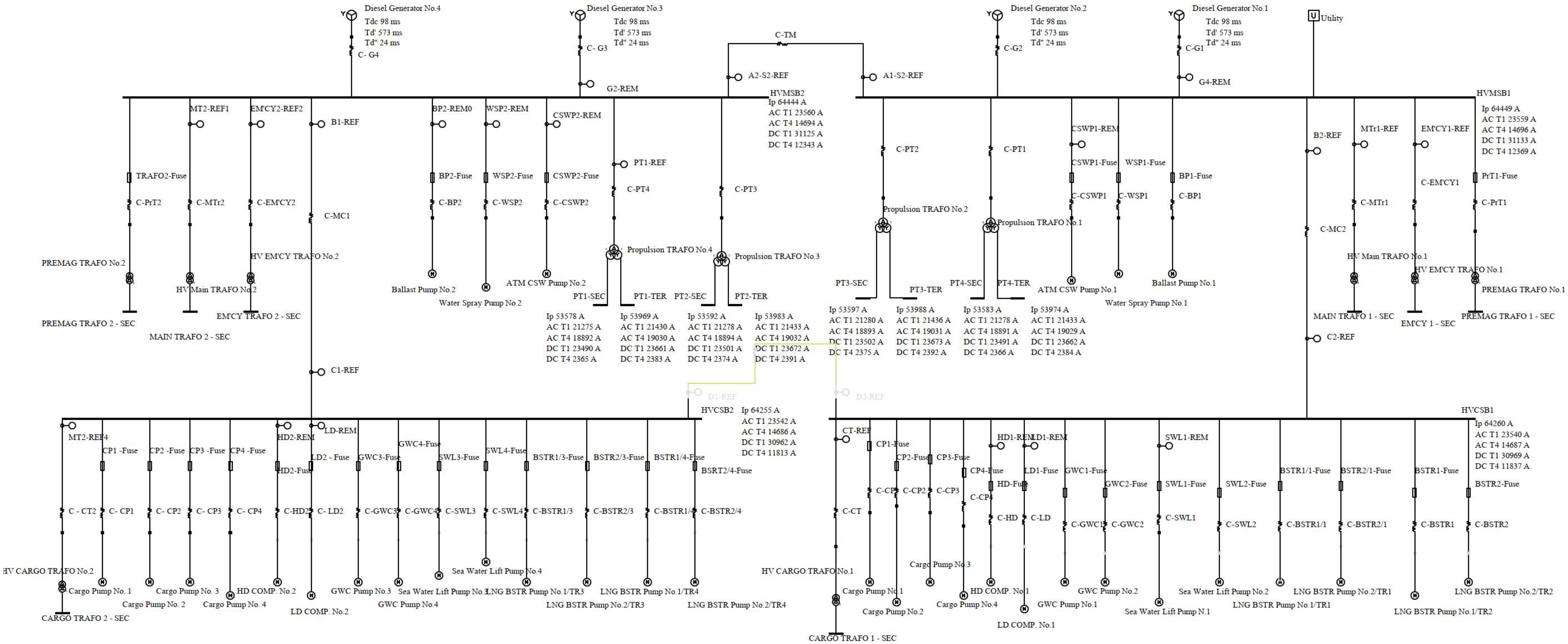


Figure 9 – SKM model for calculation of maximum short-circuit currents

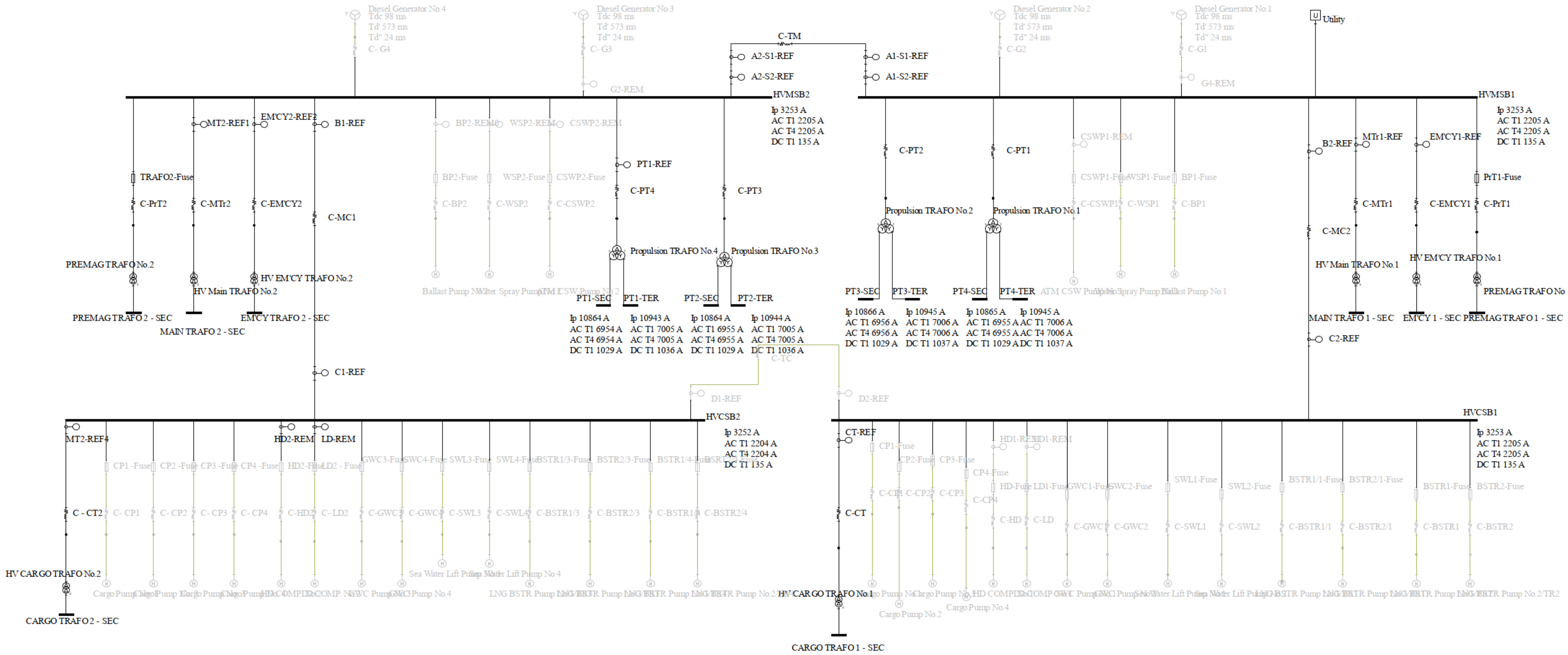


Figure 10 – SKM model for calculation of minimum short-circuit currents

5.3 CALCULATION RESULTS

Table 4 – Maximum fault currents

		Fault currents Ik IEC 61363 [kA]			
Bus name	**Voltage [V]**	**Ip 0.5 cyc. T = 8.3 ms [kA]**	**Iac 0.5 cyc. T1 = 8.3 ms [kA]**	**Idc 0.5 cyc. T1 = 8.3 ms [kA]**	**Iasym 2.7 cyc. T2 = 45 ms [kA]**
HVMSB 1	6600	64.45	23.56	31.13	25.55
HVMSB 2	6600	64.44	23.56	31.13	25.55
HVCSB 1	6600	64.26	23.54	30.96	25.17
HVCSB 2	6600	64.26	23.54	30.96	25.17

Asymmetrical short-circuit current was calculated using known values of AC and DC components:

$$I_{asym} = \sqrt{I_{ac}^2 + I_{dc}^2} \tag{1}$$

Disproportion between AC and DC components (DC component is greater) is mainly caused by a large number of motors in considering configuration.

Peak values I_p must be compared with switchboard making capacity and asymmetrical values I_{asym} are to be compared with switchboard breaking capacity, respectively.

Table 5 – Minimum fault currents

		Fault currents Ik IEC 60909 [kA]	
Bus name	**Voltage [V]**	**$Ik^{(3)}_{min}$**	**$Ik^{(2)}_{min}$**
HVMSB 1	6600	3.25	2.81
HVMSB 2	6600	3.25	2.81
HVCSB 1	6600	3.25	2.81
HVCSB 2	6600	3.25	2.81

Three-phase minimum short-circuit current was converted into two-phase short-circuit current using the following equation :

$$Ik_{min}^{(2)} = Ik_{min}^{(3)} \cdot \frac{\sqrt{3}}{2} \tag{2}$$

Obtained peak values (I_p) and three-phase minumim fault currents ($Ik^{(3)}_{min}$) are going to be used for further feeder overcurrent, short circuit protection proposal and plotting of selectivity charts.

6. PROTECTION FUNCTION PROPOSAL AND SETTING

Ballast Pump No.2 , HD Compressor No.2, Sea Water Lift Pump No.1 have been chosen for setting up a relay protection according to various protection functions. These functions are listed below.

Table 6 – Description of protection functions

Protective function	Description	Application
PHIPTOC1	Three-phase non-directional overcurrent protection, instantaneous stage	All motors
PHLPTOC1	Three-phase non-directional overcurrent protection, low stage	All motors
JAMPTOC1	Motor load jam protection	All motors
STTPMSU1	Motor start-up supervision	All motors
MNSPTOC	Negative-sequence overcurrent protection for machines	All motors
PHPTUV	Three-phase undervoltage protection	All motors
LOFLPTUC	Loss of load supervision	Sea Water Lift Pump No.1

Necessary data for all chosen motors is given in Appendices III-V.

LOFLTOC protective function has been chosen only for Sea Water Lift Pump No.1 because it is not allowed to run Sea Water lift pump pump without pumped media, due to pump cooling reasons.

Earth fault protection is not included in the protection function list, the earth fault is only alarmed at LNG vessel’s main power distribution system.

6.1 PHIPTOC1 and PHLPTOC1

The three-phase non-directional overcurrent protection function PHxPTOC is used as one-phase, two-phase or three-phase non-directional overcurrent and short-circuit protection.

The function starts when the current exceeds the set limit. The operate time characteristics for low stage PHLPTOC and high stage PHHPTOC can be selected to be either definite time or inverse definite minimum time. The instantaneous stage PHIPTOC always operates with the DT characteristic.

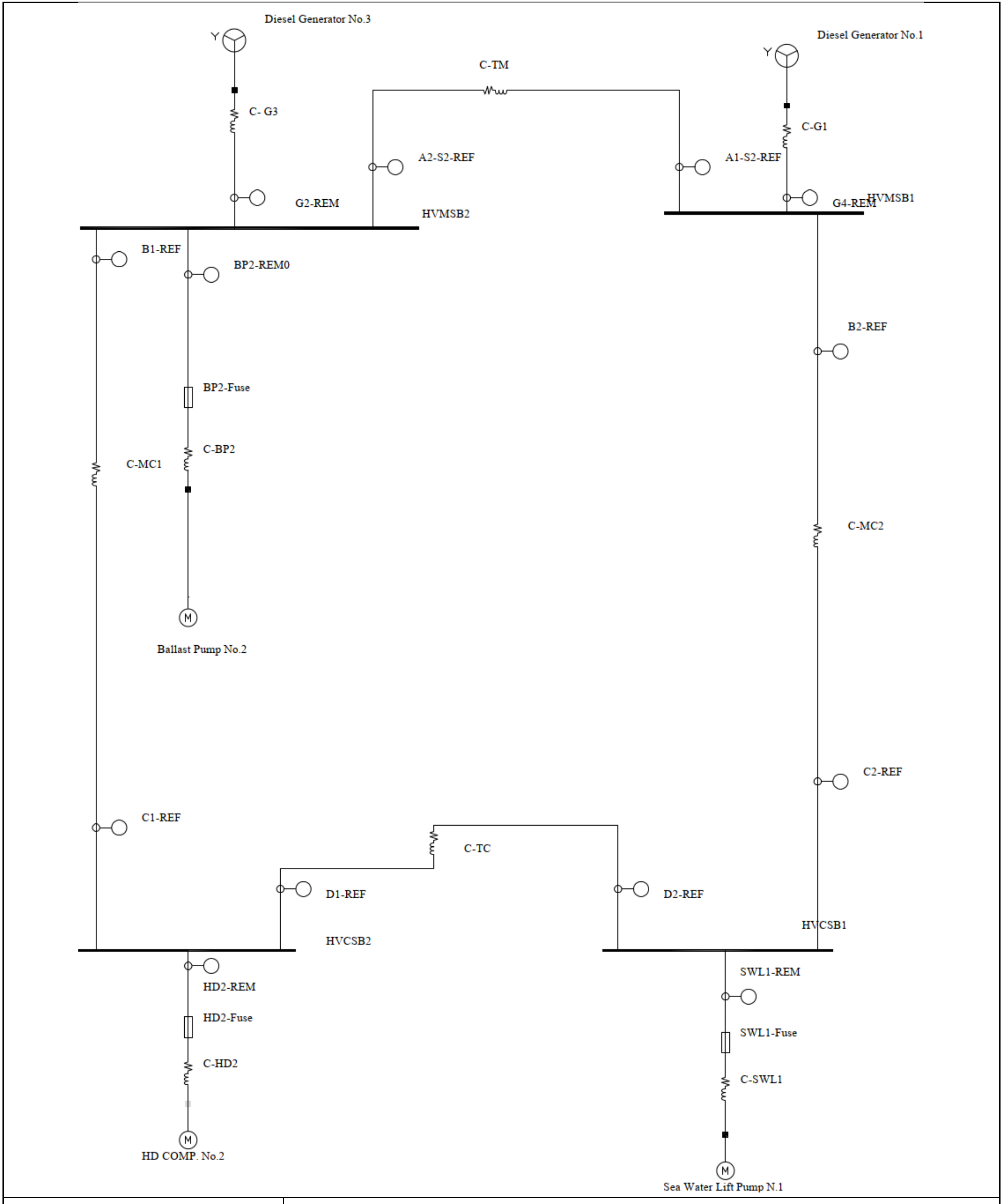
In the DT mode, the function operates after a predefined operate time and resets when the fault current disappears. The IDMT mode provides current-dependent timer characteristics.

The function contains a blocking functionality. It is possible to block function outputs, timers or the function itself, if necessary [8,11].

All TCCs were plotted in PTW software according to pre-defined data of eqipment and its basic configurations (see Appendix I).

All set values of chosen IED REM 615 are given in black boxes right on charts.

Configuration of network and its specification with chosen motors is shown below. Chart 11 describes all curves which were used for protection setting and represents the interconnection of equipment between each other. For setting up a relay protection for all motors, the longest paths from generators have been chosen.



Curve	Description
Generator No.3	Decrement Curve of Generator 3
Generator No.1	Decrement Curve of Generator 1
A2-S2-REF	Overcurrent Trip of Main-Main Transfer Breaker

Continuation of Figure 11

A1-S2-REF	Overcurrent Trip of Main-Main Transfer Breaker
G2-REM	Overcurrent Trip of Generator 3
G4-REM	Overcurrent Trip of Generator 1
C-TM	Short-Circuit Withstand Curve for Main-Main Transfer Cable
C-G3	Short-Circuit Withstand Curve for Generator 3 Cable
C-G1	Short-Circuit Withstand Curve for Generator 1 Cable
B1-REF	Overcurrent Trip of Main-Cargo Transfer Breaker
BP2-REM	Overcurrent Trip of Ballast Pump No.2
C-BP2	Short-Circuit Withstand Curve for Ballast Pump No.2 Cable
B2-REF	Overcurrent Trip of Main-Cargo Transfer Breaker
C-MC1	Short-Circuit Withstand Curve for Main-Cargo Transfer Cable
C-MC2	Short-Circuit Withstand Curve for Main-Cargo Transfer Cable
C1-REF	Overcurrent Trip of Main-Cargo Transfer Breaker
C2-REF	Overcurrent Trip of Main-Cargo Transfer Breaker
D1-REF	Overcurrent Trip of Cargo-Cargo Transfer Breaker
D2-REF	Overcurrent Trip of Cargo-Cargo Transfer Breaker
C-TC	Short-Circuit Withstand Curve for Cargo-Cargo Transfer Cable
HD2-REM	Overcurrent Trip of HD Compressor No.2
SWL1-REM	Overcurrent Trip of Sea Water Lift Pump No.1
C-HD2	Short-Circuit Withstand Curve for HD Compressor No.2 Cable
C-SWL1	Short-Circuit Withstand Curve for Sea Water Lift Pump No.1 Cable

Figure 11 – HV Generators, Main-Main Transfers, Main-Cargo Transfers and Cargo-Cargo Transfers

Table 7 – Summary of results for each motor according to PHLPTOC

Motor	**Parameter**	
	Start value [A]	**Operating curve type**
Ballast Pump No.2	56.7	Normal inverse k=0.2
HD Compressor No.2	115.5	Normal inverse k=0.4
Sea Water Lift Pump No.1	151.2	Normal inverse k=0.2

Table 8 - Summary of results for each motor according to PHIPTOC

Motor	**Parameter**	
	Start value [A]	**Operation delay [s]**
Ballast Pump No.2	372.6	0.2
HD Compressor No.2	759	0.2
Sea Water Lift Pump No.1	820.8	0.2

The overload protection setting of each motor , allows 5 % overload of the motor and normal IDMT curve has been chosen. Short circuit protection tripping curve then follows the starting current of the motor with time delay 200 ms. From the Figures 12,13,14 is clear that the short circuit on the motor feeder will be cleared by the fuse inside the *V-contactor*. This is desired, as the breaking capacity of the *V-contacto*r is 4 kA according to catalogue value [15].

For generator protection and transfer protection has been marine standard setting used.

Protection seting of these feeders exceeds extent of this thesis.

From the charts can be seen, that :

- chosen tripping charasteristics of the motor feeders allow starting of the motor
- selectivity of the motor feeder protection with upstream transfer and generator breaker is obtained
- the motor cable is protected from thermal overload caused by short circuit current

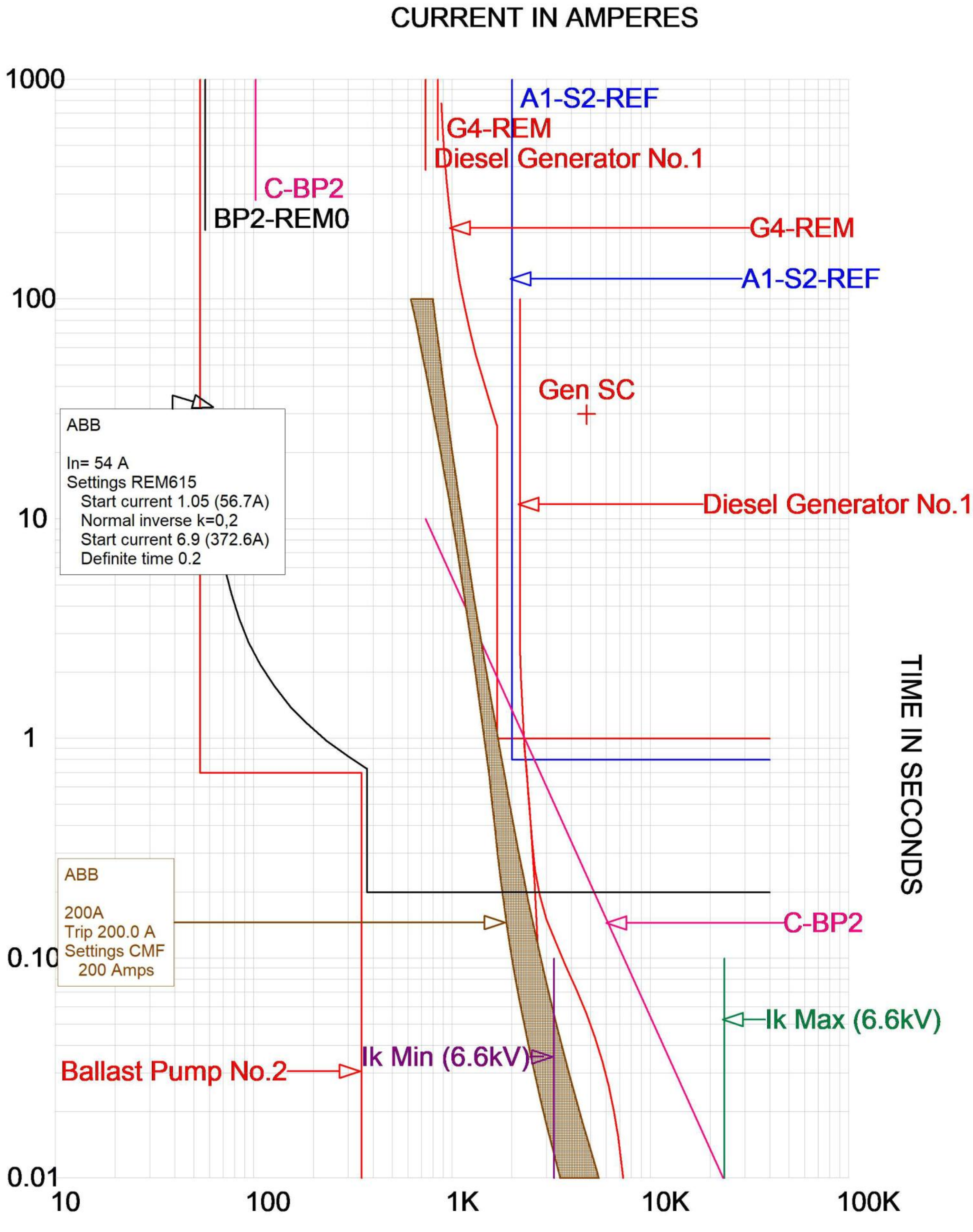


Figure 12 – TCCs for Ballast Pump No.2 protection setting

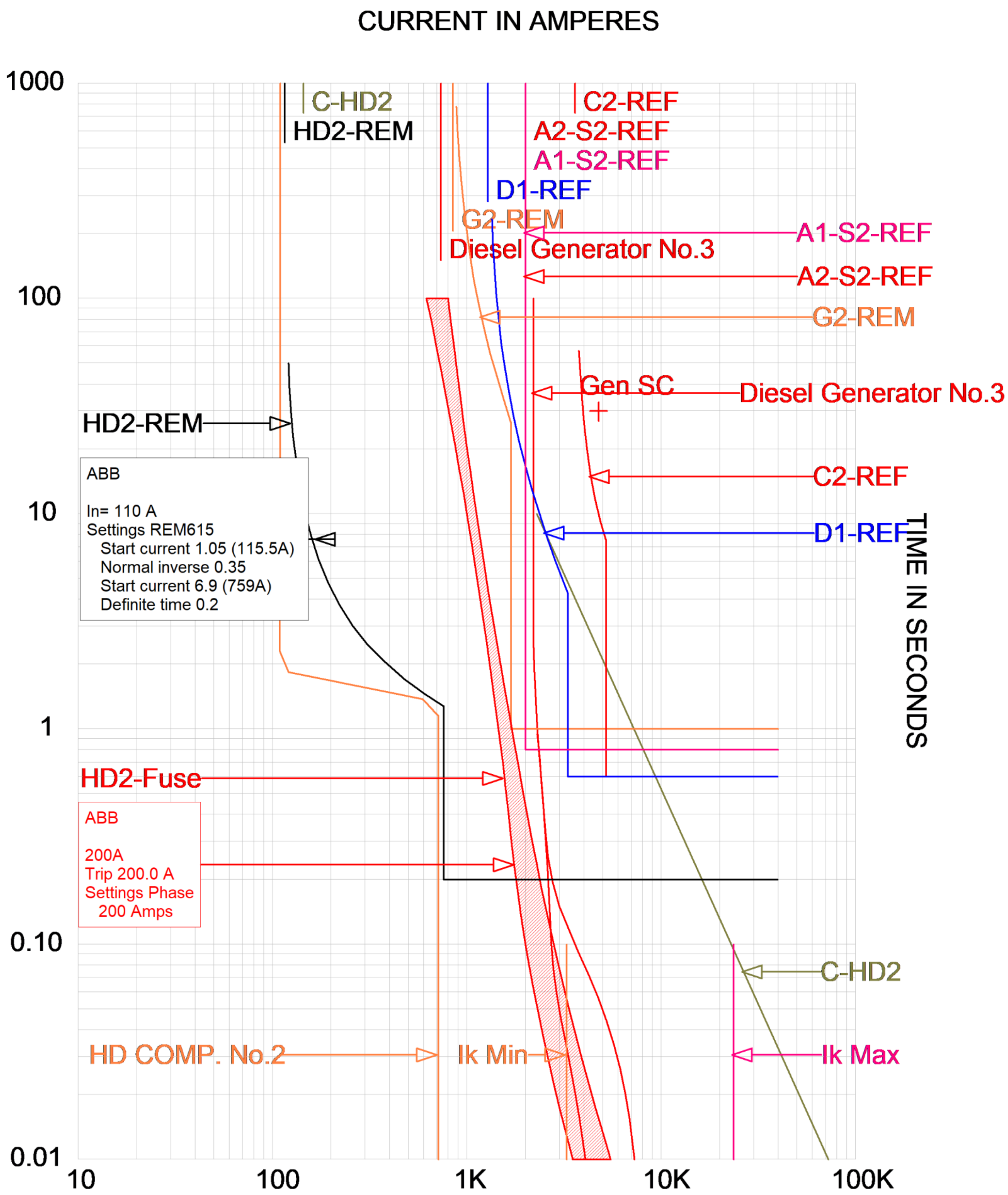


Figure 13 – TCCs for HD Compressor No.2 protection setting

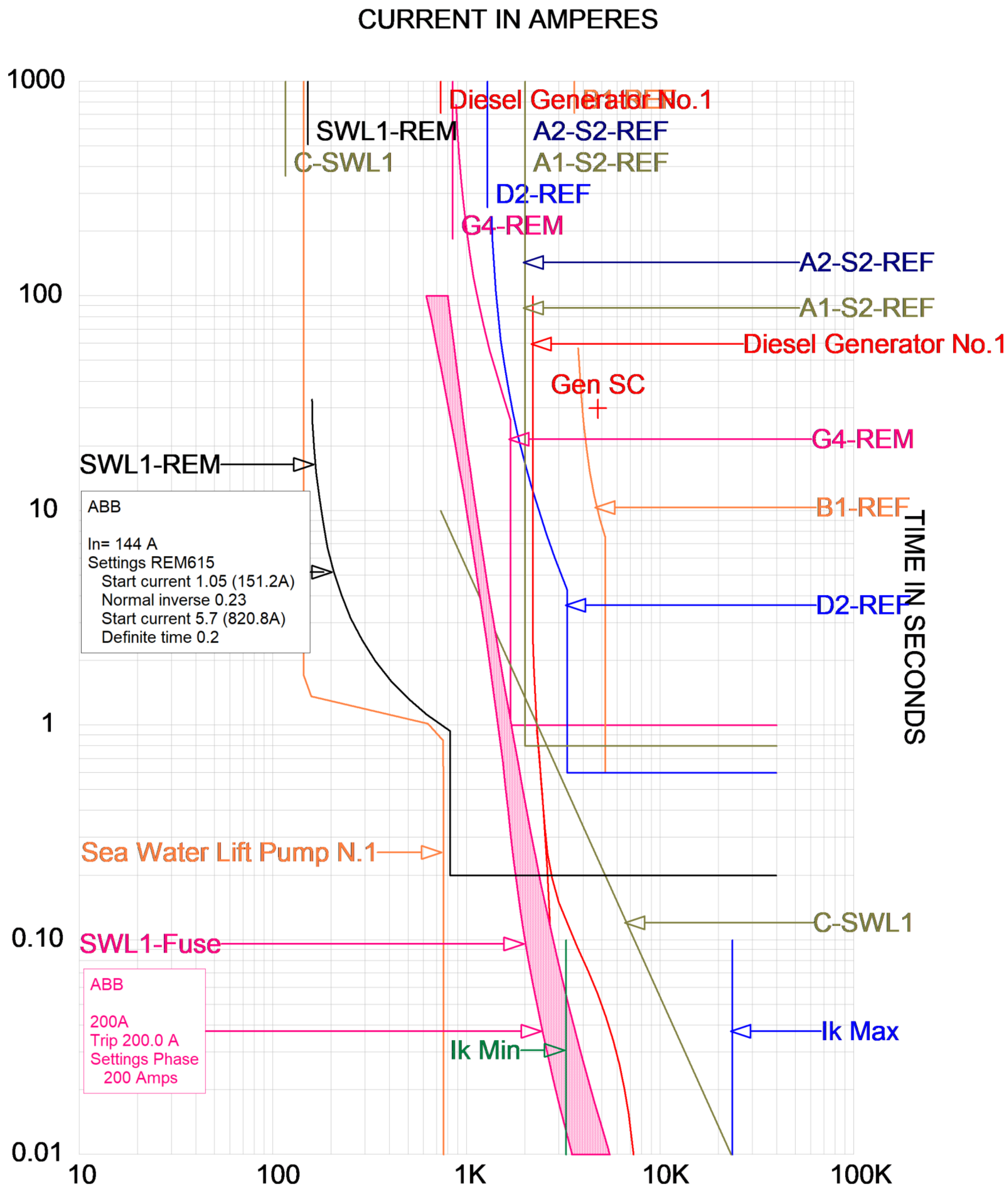


Figure 14 – TCCs for Sea Water Lift Pump No.1 protection setting

6.2 JAMPTOC1

The motor load jam protection function JAMPTOC is used for protecting the motor in stall or mechanical jam situations during the running state.

When the motor is started, a separate function is used for the startup protection, and JAMPTOC is normally blocked during the startup period and does not operate. When the motor has passed the starting phase, JAMPTOC monitors the magnitude of phase currents. The function starts when the measured current exceeds the breakdown torque level, that is, above the set limit. The operation characteristic is definite time.

The function contains a blocking functionality. It is possible to block the function outputs [8,11].

Two seconds have been chosen as an *Operation Time delay* value, it must be shorter than Maximum motor stall time (Appendicies III-V); *Start Value of Current* is equal to three times rated current (see Appendices III-V), that is 160.8 A for Ballast Pump No.2, 328.5 A for HD Compressor No.2 and 144 A for Sea Water Lift Pump No.1.

Table 9 - Summary of results for each motor according to JAMPTOC1

Motor	Parameter		
	Start value $3 \cdot I_n$ [A]	**Operation delay [s]**	**Maximum motor stall time [s]**
Ballast Pump No.2	160.8	2	28
HD Compressor No.2	328.5	2	14.5
Sea Water Lift Pump No.1	432	2	7

6.3 STTPMSU1

The motor start-up supervision function STTPMSU is designed for protection against excessive starting time and locked rotor conditions of the motor during starting. For a good and reliable operation of the motor, the thermal stress during the motor starting is maintained within the allowed limits.

The starting of the motor is supervised by monitoring the TRMS magnitude of all the phase currents or by monitoring the status of the circuit breaker connected to the motor.

During the start-up period of the motor, STTPMSU calculates the integral of the I^2t value. If the calculated value exceeds the set value, the operate signal is activated. STTPMSU has the provision to check the locked rotor condition of the motor using the speed switch, which means checking if the rotor is able to rotate or not. This feature operates after a predefined operating time.

STTPMSU also protects the motor from an excessive number of start-ups. Upon exceeding the specified number of start-ups within certain duration (see Appendicies III-V and Table 10), STTPMSU blocks further starts [8,11].

6.3.1 HD Compressor No.2

By initiating three successive starts we reach the situation as shown below. As a result, the value of the register adds up to a total of 6.9 seconds. Right after the third start has been initiated, the output lock of start of motor is activated and the fourth start will not be allowed, provided the time limit has been set to 5 seconds.

Setting of cumulative time limit:

$$\sum t_{si} = (n-1) \cdot t + margin \tag{3}$$

where n – specified maximum allowed number of motor start-ups;

t – start-up time of the motor [s]

margin – safety margin (~ 10…20 percent)

$$\sum t_{si} = (n-1) \cdot t + margin = (3-1) \cdot 2.3 = 2 \cdot 2.3 + margin \approx 5\ s$$

A maximum of three starts in 80 minutes means that the value of the register should reach the set start time counter limit within 80 minutes to allow a new start.

Setting of Counter Red Rate:

$$\Delta \sum t_s = \frac{t}{t_{reset}} \tag{4}$$

where t – specified start time of the motor [s];

t_{reset} – duration during which the maximum number of motor start-ups stated by the manufacturer can be made [h]

$$\Delta \sum t_s = \frac{t}{t_{reset}} = \frac{2.3}{\frac{80}{60}} = \frac{2.3}{1.33} = 1.7\ s/h$$

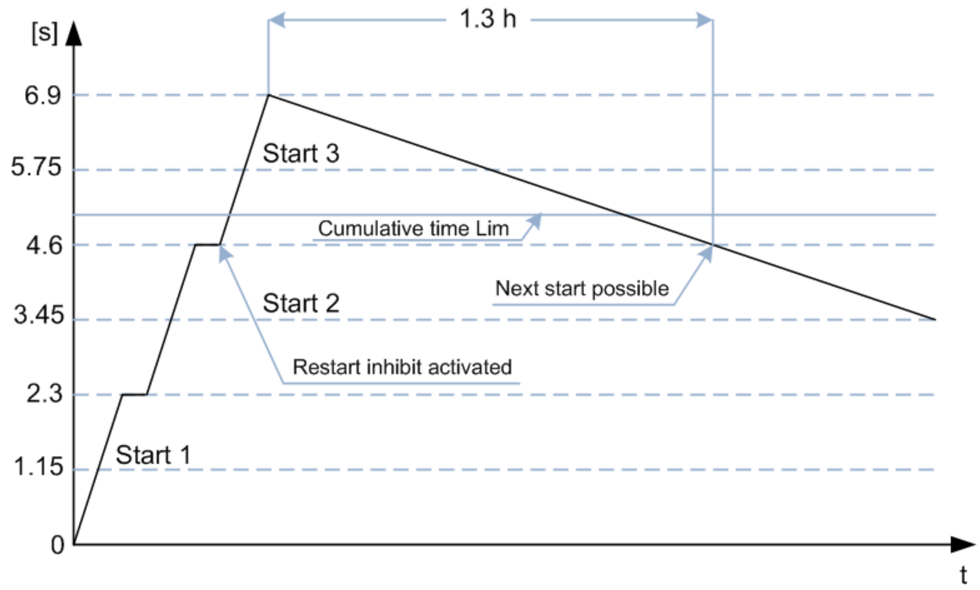


Figure 15 – HD Compressor-starting and capability curves

6.3.2 Ballast Pump No.2

By initiating three successive starts we reach the situation as shown below. As a result, the value of the register adds up to a total of 2.1 seconds. Right after the third start has been initiated, the output lock of start of motor is activated and the fourth start will not be allowed, provided the time limit has been set to 1.6 seconds.

Setting of cumulative time limit:

$$\sum t_{si} = (n-1) \cdot t + margin = (3-1) \cdot 0.7 + margin = 2 \cdot 0.7 + margin \approx 1.6\ s$$

A maximum of three starts in 40 minutes means that the value of the register should reach the set start time counter limit within 40 minutes to allow a new start.

Setting of Counter Red Rate:

$$\Delta \sum t_s = \frac{t}{t_{reset}} = \frac{0.7}{\frac{40}{60}} = \frac{0.7}{0.667} \approx 1\ s/h$$

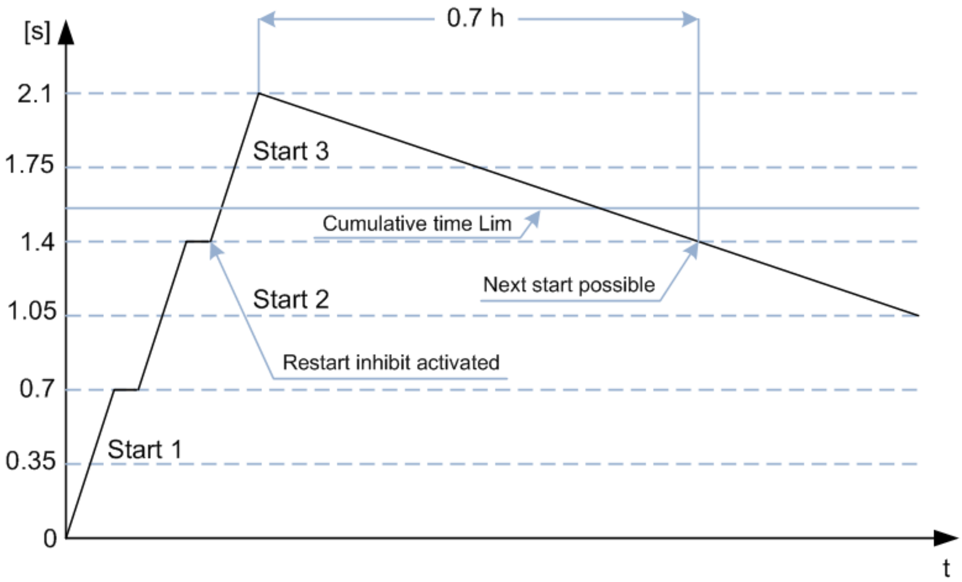


Figure 16 – Ballast Pump-starting and capability curves

6.3.3 Sea Water Lift Pump No.1

By initiating three successive starts we reach the situation as shown below. As a result, the value of the register adds up to a total of 5.1 seconds. Right after the third start has been initiated, the output lock of start of motor is activated and the fourth start will not be allowed, provided the time limit has been set to 4 seconds.

Setting of cumulative time limit:

$$\sum t_{si} = (n-1) \cdot t + margin = (3-1) \cdot 1.7 + margin = 2 \cdot 1.7 + margin \approx 4\ s$$

A maximum of three starts in 80 minutes means that the value of the register should reach the set start time counter limit within 80 minutes to allow a new start.

Setting of Counter Red Rate:

$$\Delta\sum t_s = \frac{t}{t_{reset}} = \frac{1.7}{\frac{80}{60}} = \frac{1.7}{1.333} \approx 1.3\ s/h$$

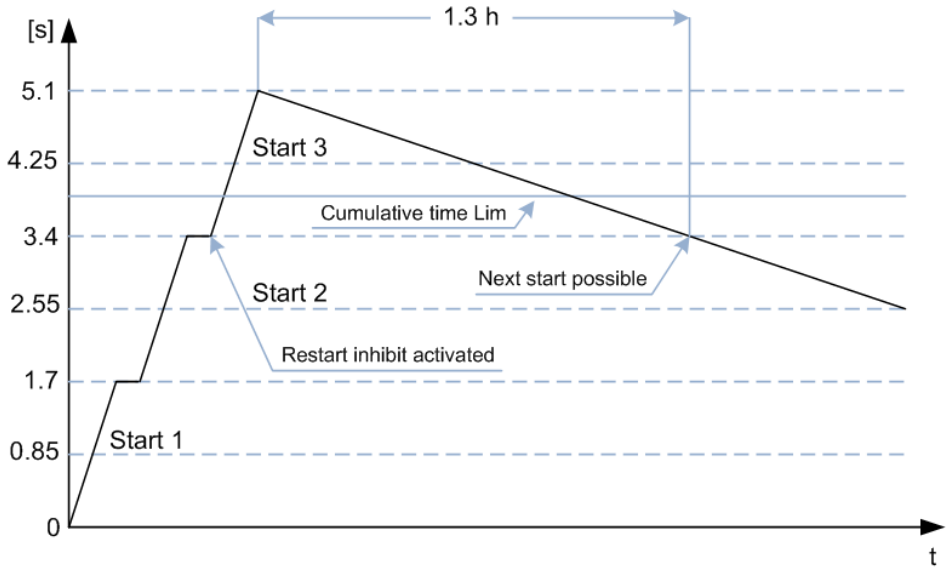


Figure 17 – Sea Water Lift Pump-starting and capability curves

Table 10 - Summary of results for each motor according to STTPMSU1

Motor	Parameter			
	Cumulative time Lim [s]	Counter Red Rate [s/h]	Allowed number of starts	
			Cold	Hot
Ballast Pump No.2	1.6	1	3	2
HD Compressor No.2	5	1.7	3	2
Sea Water Lift Pump No.1	4	1.3	3	2

6.4 MNSPTOC1

In a three-phase motor, the conditions that can lead to unbalance are single phasing, voltage unbalance from the supply and single-phase fault. The negative sequence current damages the motor during the unbalanced voltage condition, and therefore the negative sequence current is monitored to check the unbalance condition.

When the voltages supplied to an operating motor become unbalanced, the positive-sequence current remains substantially unchanged, but the negative-sequence current flows due to the unbalance. For example, if the unbalance is caused by an open circuit in any phase, a negative-sequence current flows and it is equal and opposite to the previsous load current in a healthy phase.

The combination of positive and negative-sequence currents produces phase currents approximately 1.7 times the previous load in each healthy phase and zero current in the open phase.

The negative-sequence overcurrent protection for machines function MNSPTOC protects electric motors from phase unbalance. A small voltage unbalance can produce a large negative sequence current flow in the motor. For example, a 5 percent voltage unbalance produces a stator negative-sequence current of 30 percent of the full load current, which can severely heat the motor. MNSPTOC detects the large negative sequence current and disconnects the motor [8,11].

Maximum continuous negative sequence is typically 10 % of nominal current (see Appendices III-V), so 8 % has been set up to each motor. The protection relay provides two user-programmable Inverse Definite Minimum Time characteristics curves, *"Inverse curve A"* and *"Inverse curve B"* [8]. Curve B has been chosen because it is triggered by fault faster than the type A.

Table 11 – Summary of results for each motor according to MNSPTOC1

Motor	**Parameter**	
	Start value $0.08 \cdot I_n$ [A]	**Operating curve type**
Ballast Pump No.2	4.3	Inverse Curve B
HD Compressor No.2	8.8	Inverse Curve B
Sea Water Lift Pump No.1	11.5	Inverse Curve B

6.5 PHPTUV

System Undervoltage occurs when the system is overloaded and when a problem of generator excitation exists. The main task and basic function of Undervoltage Protection Corrdination is to disconnect less important consumers before more important ones. The three-phase undervoltage protection function PHPTUV is used to disconnect from the network devices, for example electric motors, which are damaged when subjected to service under low voltage conditions. PHPTUV includes a settable value for the detection of undervoltage either in a single phase, two phases or three phases.

Generally transfers (busties) are disconnected the first, then motor pump feeders, then propulsion transformers, distribution transformers and then, finally, generators.

PHPTUV is applied to power system elements, such as generators, transformers, motors and power lines, to detect low voltage conditions. Low voltage conditions are caused by abnormal operation or a fault in the power system. PHPTUV can be used in combination with overcurrent protections. PHPTUV is also used to initiate voltage correction measures, to compensate for a reactive load and thereby to increase the voltage [8,11].

Undervoltage protection has been set up to 70 % of the rated voltage, as it is required by Class Society [14].

Time delay equals to 3 s has been chosen for motors, which allows shorter time delay for transfers and longer delay for transformer and generator feeders. Setting of these feeders exceeds extent of this thesis but the undervoltage situation should be cleared within 5 s in vessel distribution network.

Table 12 - Summary of results for each motor according to PHPTUV

Motor	Parameter	
	Start value $0.7 \cdot U_n$ [V]	**Operation delay [s]**
Ballast Pump No.2	4620	3
HD Compressor No.2	4620	4
Sea Water Lift Pump No.1	4620	3

6.6 LOFLPTUC

The loss of load supervision function LOFLPTUC is used to detect a sudden load loss which is considered as a fault condition.

LOFLPTUC starts when the current is less than the set limit. It operates with the definite time characteristics, which means that the function operates after a predefined operate time and resets when the fault current disappears.

LOFLPTUC detects the condition by monitoring the current values and helps disconnect the motor from the power supply instantaneously or after a delay according to the requirement.

When the motor is at standstill, the current will be zero and it is not recommended to activate the trip during this time. The minimum current drawn by the motor when it is connected to the power supply is the no load current, that is, the higher start value current. If the current drawn is below the lower start value current, the motor is disconnected from the power supply. LOFLPTUC detects this condition and interprets that the motor is de-energized and disables the function to prevent unnecessary trip events.

Start value high equals to 60 % of rated current of protected motor and it equals to 86.4 A for Sea Water Lift Pump No.1 [8,11].

Start value low equals to 10 % of rated current of protected motor and it equals to 14.4 A for Sea Water Lift Pump No.1 [8,11].

Five seconds have been chosen as a *Time delay* value.

Table 13 - Summary of results for each motor according to LOFLPTUC

Motor	Parameter		
	Start value low $0.1 \cdot I_n$ [A]	**Start value high $0.6 \cdot I_n$ [A]**	**Operation delay [s]**
Sea Water Lift Pump No.1	14.4	86.4	5

CONCLUSION

The main aim of this thesis is to propose setting of three 6.6 kV motor feeders at LNG carrier according to IEC requirements and applicable Marine Class rules.

Based on applicable standards and regulations following protection has been chosen, ensuring safe and reliable feeder operation on board the vessel: overload, short circuit, undervoltage, motor load jam protection, motor start-up supervision and loss of load supervision

Medium voltage power system of the LNG carrier has been modelled in the SKM Power Tools software and short circuit calculation has been performed according to IEC 61363 standard, which is applicable for marine industry. Calculation results were then used in overcurrent and short circuit tripping charts for verification of the selectivity with upstream breakers and for verification of the motor cable protection. Proposed overcurrent and short circuit protection relay settings ensures selectivity with upstream breakers, ensures motor start with the nominal load and also ensures protection of the motor and its power supply cable.

Motor load jam protection function setting was implemented on the basis of input data for each motor, taking into account maximum motor stall time.

For motor start-up supervision function setting, all necessary calculations for finding basic parameters such as *Cumulative Time Limit* and *Counter Red Rate* have been carried out and proposed settings of the start supervision allows 3 consecutive starts from cold condition and 2 starts in hot condition as it is given by the motor supplier. Protection function will block additional starts above such limit.

Negative-sequence, undervoltage and loss of load supervision protection functions setting was implemented on the basis of input data for each motor and applicable Marine Class rules. Undervoltage protection setting proposal is based on ABS marine class regulation with time delay ensuring selectivity with other MV feeders in power system.

In this thesis proposed protection settings sufficiently and selectively protects motors and their power supply cables according to applicable IEC standards, marine class rules and motor manufacturer requirements.

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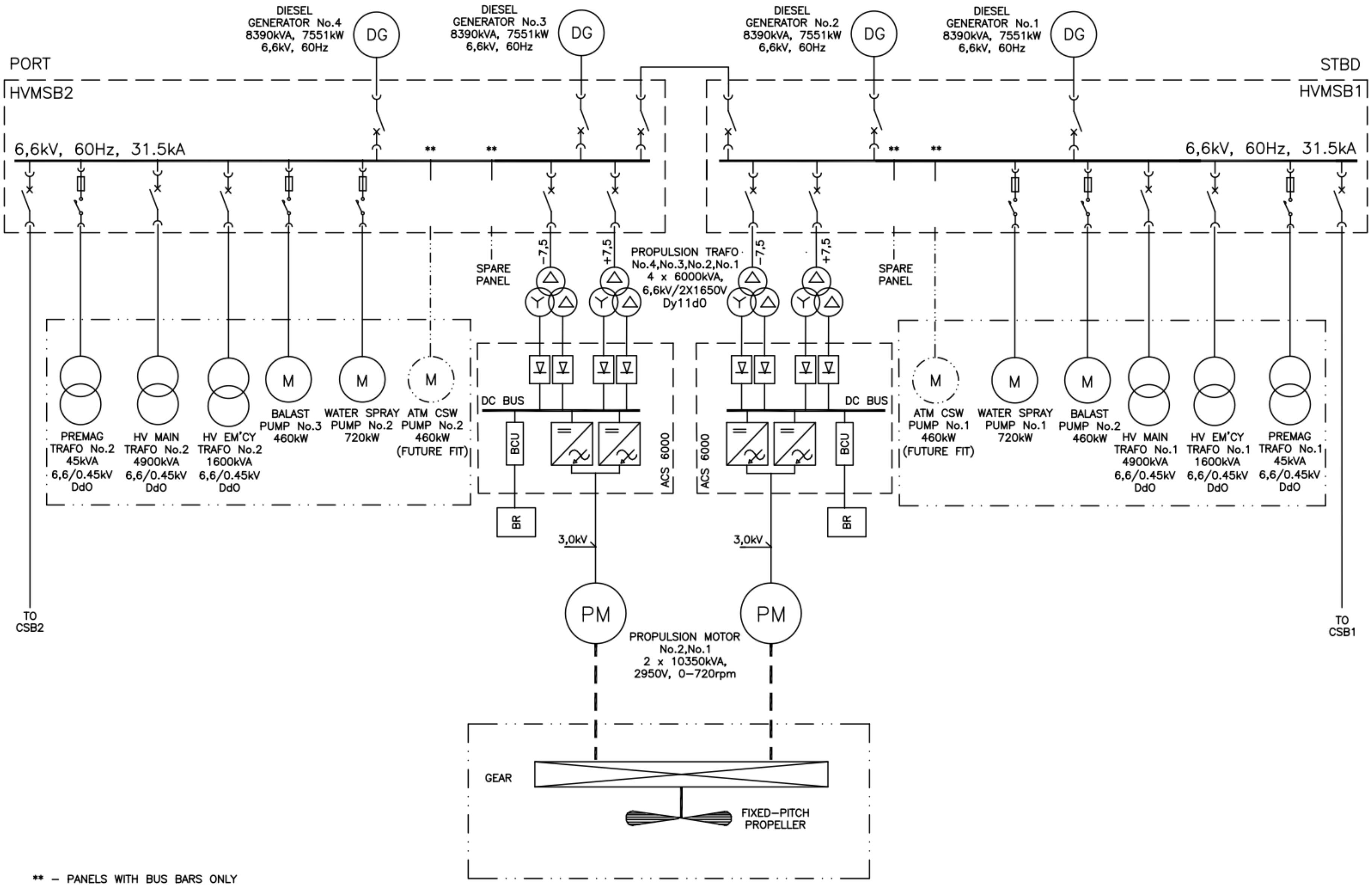
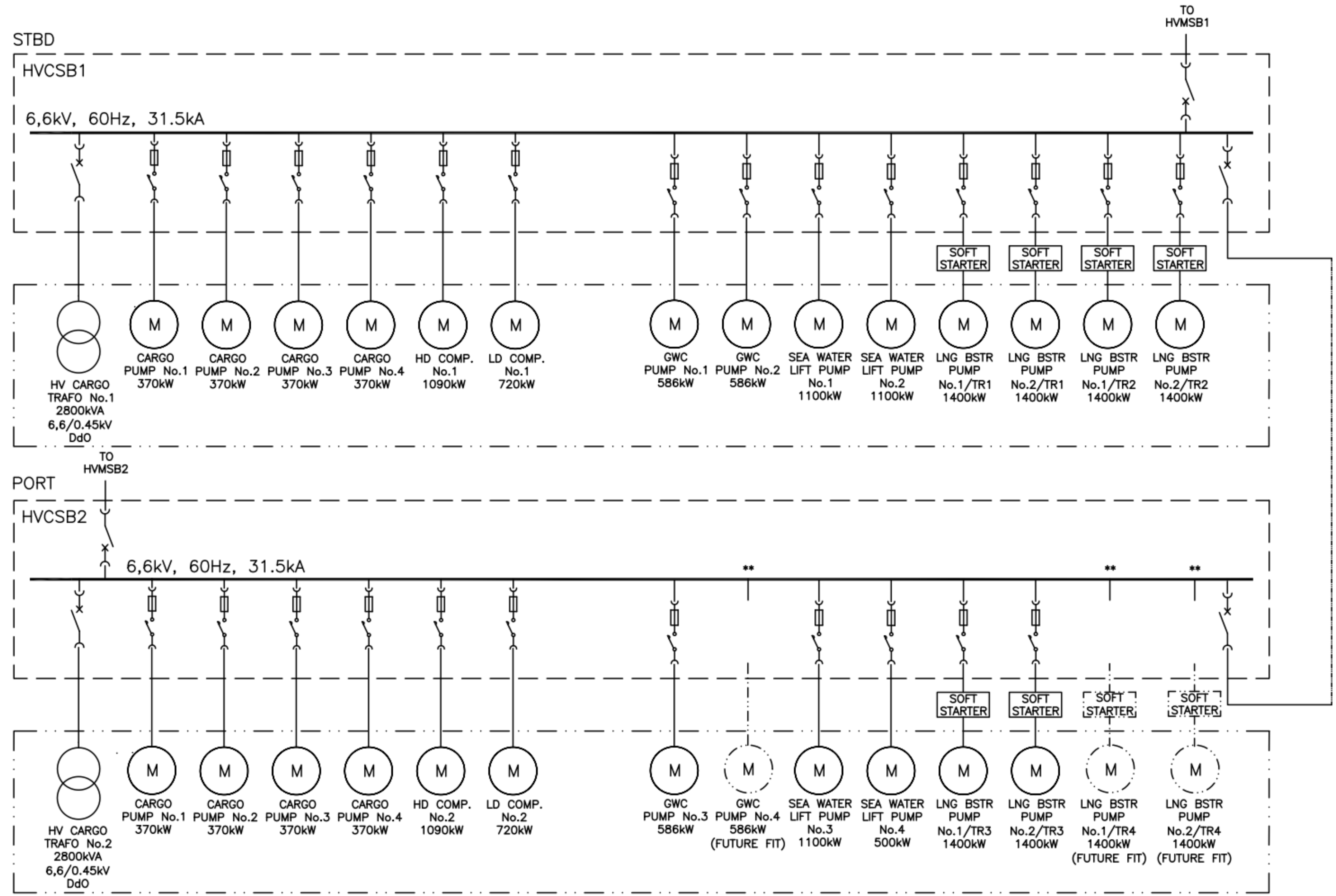
APPENDIX I – Single-line diagram of 6,6 kV Main&Cargo Switchboards



** – PANELS WITH BUS BARS ONLY



** – PANELS WITH BUS BARS ONLY

APPENDIX II – 6,6 kV cable data

Table 8 – 6.6 kV cable data

Number of cores and area [mm²]	Number of parallel per phase	Estimated length [m]	Connection	
			From	To
3x120	4	41	No.1 6.6 kV Main SWBD	6.6 kV Generator #1
3x120	4	33	No.1 6.6 kV Main SWBD	6.6 kV Generator #2
3x120	8	12	No.1 6.6 kV Main SWBD	No.2 6.6 kV Main SWBD
3x120	3	21	No.1 6.6 kV Main SWBD	No.1 Propulsion Tr
3x120	3	19	No.1 6.6 kV Main SWBD	No.2 Propulsion Tr
3x120	16	26	No.1 6.6 kV Main SWBD	No.1 6.6 kV Cargo SWBD
3x95	3	11	No.1 6.6 kV Main SWBD	No.1 6.6 kV Main Tr (4900 kVA)
3x70	1	38	No.1 6.6 kV Main SWBD	No.1 HV EM'CY tr(1600 kVA)
3x35	1	35	No.1 6.6 kV Main SWBD	No.1 Atom Cond. CSW Pump
3x35	1	35	No.1 6.6 kV Main SWBD	No.2 Ballast Pump
3x35	1	36	No.1 6.6 kV Main SWBD	No.1 Water Spray Pump
3x35	1	17	No.1 6.6 kV Main SWBD	No.1 PREMAG Tr
3x120	4	35	No.2 6.6 kV Main SWBD	6.6 kV Generator #3
3x120	4	41	No.2 6.6 kV Main SWBD	6.6 kV Generator #4
3x120	3	19	No.2 6.6 kV Main SWBD	No.3 Propulsion Tr
3x120	3	21	No.2 6.6 kV Main SWBD	No.4 Propulsion Tr
3x120	16	26	No.2 6.6 kV Main SWBD	No.2 6.6 kV Cargo SWBD
3x95	3	13	No.2 6.6 kV Main SWBD	No.2 6.6 kV Main Tr (4900 kVA)
3x70	1	41	No.2 6.6 kV Main SWBD	No.2 HV EM'CY Tr (1600 kVA)
3x35	1	35	No.2 6.6 kV Main SWBD	No.2 Atom Cond. CSW Pump
3x35	1	35	No.2 6.6 kV Main SWBD	No.3 Ballast Pump

Continuation of Table 8

3x35	1	35	No.2 6.6 kV Main SWBD	No.2 Water Spray Pump
3x35	1	17	No.2 6.6 kV Main SWBD	No.2 PREMAG Tr
3x120	8	33	No.1 6.6 kV Cargo SWBD	No.2 6.6 kV Cargo SWBD
3x95	2	17	No.1 6.6 kV Cargo SWBD	No.1 6.6 kV Cargo Tr (2800 kVA)
3x35	1	192	No.1 6.6 kV Cargo SWBD	No.1 Cargo Pump for No.1 C/T
3x35	1	140	No.1 6.6 kV Cargo SWBD	No.1 Cargo Pump for No.2 C/T
3x35	1	91	No.1 6.6 kV Cargo SWBD	No.1 Cargo Pump for No.3 C/T
3x35	1	39	No.1 6.6 kV Cargo SWBD	No.1 Cargo Pump for No.4 C/T
3x70	1	55	No.1 6.6 kV Cargo SWBD	No.1 High Duty Compressor
3x35	1	65	No.1 6.6 kV Cargo SWBD	No.1 Low Duty Compressor
3x95	1	13	No.1 6.6 kV Cargo SWBD	No.1 Regas Skid Booster PP No.1 Soft Starter
3x95	1	13	No.1 6.6 kV Cargo SWBD	No.1 Regas Skid Booster PP No.2 Soft Starter
3x95	1	16	No.1 6.6 kV Cargo SWBD	No.2 Regas Skid Booster PP No.1 Soft Starter
3x95	1	15	No.1 6.6 kV Cargo SWBD	No.2 Regas Skid Booster PP No.2 Soft Starter
3x35	1	249	No.1 6.6 kV Cargo SWBD	No.1 Regas Skid GWC PP
3x35	1	254	No.1 6.6 kV Cargo SWBD	No.2 Regas Skid GWC PP
3x95	1	273	No.1 6.6 kV Cargo SWBD	Sea Water Lift Pump No.1
3x95	1	276	No.1 6.6 kV Cargo SWBD	Sea Water Lift Pump No.2
3x95	2	20	No.2 6.6 kV Cargo SWBD	No.2 6.6 kV Cargo Tr (2800kva)
3x35	1	192	No.2 6.6 kV Cargo SWBD	No.2 Cargo Pump for No.1 C/T
3x35	1	140	No.2 6.6 kV Cargo SWBD	No.2 Cargo Pump for No.2 C/T
3x35	1	93	No.2 6.6 kV Cargo SWBD	No.2 Cargo Pump for No.3 C/T
3x35	1	42	No.2 6.6 kV Cargo SWBD	No.2 Cargo Pump for No.4 C/T

End of Table 8

3x70	1	69	No.2 6.6 kV Cargo SWBD	No.2 High Duty compressor
3x35	1	83	No.2 6.6 kV Cargo SWBD	No.2 Low Duty compressor
3x95	1	14	No.2 6.6 kV Cargo SWBD	No.3 Regas Skid Booster PP No.1 Soft Starter
3x95	1	13	No.2 6.6 kV Cargo SWBD	No.3 Regas Skid Booster PP No.2 soft starter
3x95	1	13	No.2 6.6 kV Cargo SWBD	No.4 Regas Skid Booster pp No.1 Soft Starter
3x95	1	13	No.2 6.6 kV Cargo SWBD	No.4 Regas Skid Booster PP No.2 Soft Starter
3x35	1	252	No.2 6.6 kV Cargo SWBD	No.3 Regas Skid GWC PP
3x35	1	252	No.2 6.6 kV Cargo SWBD	No.4 Regas Skid GWC PP
3x95	1	277	No.2 6.6 kV Cargo SWBD	Sea Water Lift Pump No.3
3x50	1	272	No.2 6.6 kV Cargo SWBD	Sea Water Lift Pump No.4

APPENDIX III – 6,6 kV Ballast Pump No.2 data

Description	Symbol	Value	Unit	IEC ref
Rated output power (shaft)	P_r	460	kW	
Rated voltage	U_r	6,6	kV	61363-1
Rated speed	n	1188	rpm	
Rated current	I_r	53,6	A	61363-1
No load current	I_0	22,4	A	60034-2
Start current, according to starting method	I_{start}	6,5	x I_r	
Starting method (DOL/YD/Auto-trafo/Soft S.)		DOL		
Power factor at start	$\cos\phi_{start}$	0,27		
Start time (incl. driven equipment)	t_{start}	0,7	s	
Rated power factor at 100% load	$\cos\phi$	0,79		
Efficiency at 100% load	η	95	%	
Maximum stall time	t_{stall}	28,0	s	
Allowed sequential starts cold condition	cold	3		
Allowed sequential starts warm condition Warm condition assumed after 10 min running with P>0.5Pn	warm	2		
Cooling method (IC code)		IC411		60034-6
Cooling time before one more start		40	min	
Minimum time between starts		0,89	s	
Connection of stator winding		Y		
Winding capacitance (one phase to ground)	C_0	0,064	µF	
Stator resistance	r_S	0,8	%	
Stator leakage reactance	x_S	9,0	%	
Rotor resistance	r_R	1,1	%	
Rotor reactance	X_R	14,7	%	
Magnetizing reactance	Z_m	164,0	Ω	
d-axis reactance	X_d	239,7	%	
d-axis transient reactance	$X_{d'}$	16,1	%	
d-axis sub-transient reactance	$X_{d''}$	16,1	%	
d-axis transient time contant	$T_{d'}$	0,58	s	
d-axis sub-transient time constant	T_d''	0,58	s	
Max. contunuous negative sequence	$I_{(2),}max$	10	% of I_r	60034-1

APPENDIX IV – 6,6 kV HD Compressor No.2 data

Description	Symbol	Value	Unit	IEC ref
Rated output power (shaft)	P_r	1090	kW	
Rated voltage	U_r	6,6	kV	61363-1
Rated speed	n	3570	rpm	
Rated current	I_r	109,5	A	61363-1
No load current	I_0	58,7	A	60034-2
Start current, according to starting method	I_{start}	6,5	x I_r	
Starting method (DOL/YD/Auto-trafo/Soft S.)		DOL		
Power factor at start	$\cos\phi_{start}$	0,17		
Start time (incl. driven equipment)	t_{start}	2,3	s	
Rated power factor at 100% load	$\cos\phi$	0,91		
Efficiency at 100% load	η	95,7	%	
Maximum stall time	t_{stall}	14,5	s	
Allowed sequential starts cold condition	cold	3		
Allowed sequential starts warm condition Warm condition assumed after 10 min running with P>0.5Pn	warm	2		
Cooling method (IC code)		IC81W		60034-6
Cooling time before one more start		80	min	
Minimum time between starts		0,89	s	
Connection of stator winding		Y		
Winding capacitance (one phase to ground)	C_0	0,178	µF	
Stator resistance	r_S	1,0	%	
Stator leakage reactance	x_S	13,4	%	
Rotor resistance	r_R	0,8	%	
Rotor reactance	X_R	4,3	%	
Magnetizing reactance	Z_m	60,6	Ω	
d-axis reactance	X_d	187,5	%	
d-axis transient reactance	$X_{d'}$	14,3	%	
d-axis sub-transient reactance	$X_{d''}$	14,3	%	
d-axis transient time contant	$T_{d'}$	0,60	s	
d-axis sub-transient time constant	T_d''	0,60	s	
Max. contunuous negative sequence	$I_{(2),}$max	10	% of I_r	60034-1

APPENDIX V – 6,6 kV Sea Water Lift Pump No.1 data

Description	Symbol	Value	Unit	IEC ref
Rated output power (shaft)	P_r	1100	kW	
Rated voltage	U_r	6,6	kV	61363-1
Rated speed	n	710	rpm	
Rated current	I_r	144	A	61363-1
No load current	I_0	~50	A	60034-2
Start current, according to starting method	I_{start}	~5.3	x I_r	
Starting method (DOL/YD/Auto-trafo/Soft S.)		DOL		
Power factor at start	$\cos\phi_{start}$	~0.2		
Start time (incl. driven equipment)	t_{start}	~1.7	s	
Rated power factor at 100% load	$\cos\phi$	0,73		
Efficiency at 100% load	η	91,8	%	
Maximum stall time	t_{stall}	~7	s	
Allowed sequential starts cold condition	cold	3		
Allowed sequential starts warm condition Warm condition assumed after 10 min running with P>0.5Pn	warm	TBA	s	
Cooling method (IC code)		Direct oil		60034-6
Cooling time before one more start		80	min	
Minimum time between starts		b/n 2 hot consecutive starts; no waiting time	min	
Connection of stator winding		star		
Winding capacitance (one phase to ground)	C_0	TBA	µF	
Insulation class		F		60085
Stator resistance	r_S	1,17	%	
Stator leakage reactance	x_S	11,4	%	
Rotor resistance	r_R	0,82	%	
Rotor reactance	X_R	12,8	%	
Magnetizing reactance	Z_m	136	Ω	
Motor starting stator reactance	X_d	9,6	%	
Motor starting rotor reactance	$X_{d'}$	4,4	%	
d-axis transient time contant	$X_{d''}$	NA	%	
d-axis sub-transient time contant	$T_{d'}$	NA	s	
d-axis sub-transient time constant	T_d''	NA	s	
Max. contunuous negative sequence	$I_{(2),}$max	10	% of I_r	60034-1

APPENDIX VI – 8389 kVA Main Generators data

Description	Symbol	Value	Unit	IEC ref
Rated apparent power	S_r	8389	kVA	
Rated voltage	U_r	6,6	kV	61363-1
Rated speed	n	514	rpm	
Rated current	I_r	734	A	61363-1
Rated power factor	cosϕ	0.9		
Rated frequency	f_r	60	Hz	61363-1
AVR type		UN 1020		
Sustained short-circuit current		>3.0	xI_r	
Windidng capacitance	C_o	0.17	µF	
Insulation class		F		60085
Cooling method (IC code)		IC8A1W7		60034-1
d-axis sub-transient reaktance, unsaturated	$X_{d'' (u)}$		%	61363-1
d-axis sub-transient reactance, saturated	$X_{d'' (s)}$	15,4	%	61363-1
d-axis transient reactance, unsaturated	$X_{d' (u)}$		%	61363-1
d-axis transient reactance, saturated	$X_{d' (s)}$	26,4	%	61363-1
d-axis reactance, unsaturated	$X_{d (u)}$	165,6	%	61363-1
q-axis sub-transient reactance, saturated	$X_{q'' (s)}$	17,8	%	61363-1
q-axis transient reactance, saturated	$X_{q' (s)}$		%	61363-1
q-axis reactance, unsaturated	$X_{q (u)}$	87,4	%	61363-1
Zero sequence reactance	$X_{/0)}$	8,5	%	60027-4
Negative sequence reactance	$X_{(2)}$	16,6	%	60027-4
Stator winding resistance	R_a	0,42	%	61363-1
d-axis sub-transient time constant	$T_{d''}$	0,02402	s	61363-1
d-axis transient time constant	$T_{d'}$	0,573	s	61363-1
d-axis open-circuit sub-transient time constant	$T_{d0''}$	0,03895	s	61363-1
d-axis open-circuit transient time constant	$T_{d0'}$	3,267	s	61363-1
q-axis sub-transient time constant	$T_{q''}$	0,0389	s	61363-1
DC time constant	T_{dc}	0,098	s	61363-1
Max continuous negative sequence	$I_{(2), max}$	8	% of I_r	61363-1
Fault condition capability	$(I_{(2)/In)2t}$	20	s	61363-1
Required cooling time after trip	t	300	s	